ALLOY 718 and OTHER DERIVATIVES BASED ON γ'' PRECIPITATION

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I. INTRODUCTION : Alloys Strengthened by γ'' Precipitates

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- **II.1. Atomic Structure**
- **II.2. Composition**
- **II.3. Dislocations in γ'' phase**
- **II.4. Compact Morphology**
- **II.5. γ'' Shape and Coalescence**

III. MECHANICAL PROPERTIES OF INCONEL 718 (Introduction)

IV. HIGH TEMPERATURE FATIGUE OF INCONEL 718 in RELATION WITH MICROSTRUCTURE

Crack Initiation : Grain Size and Initiation from Carbide Particles

V. CONCLUSIONS & PROSPECTS

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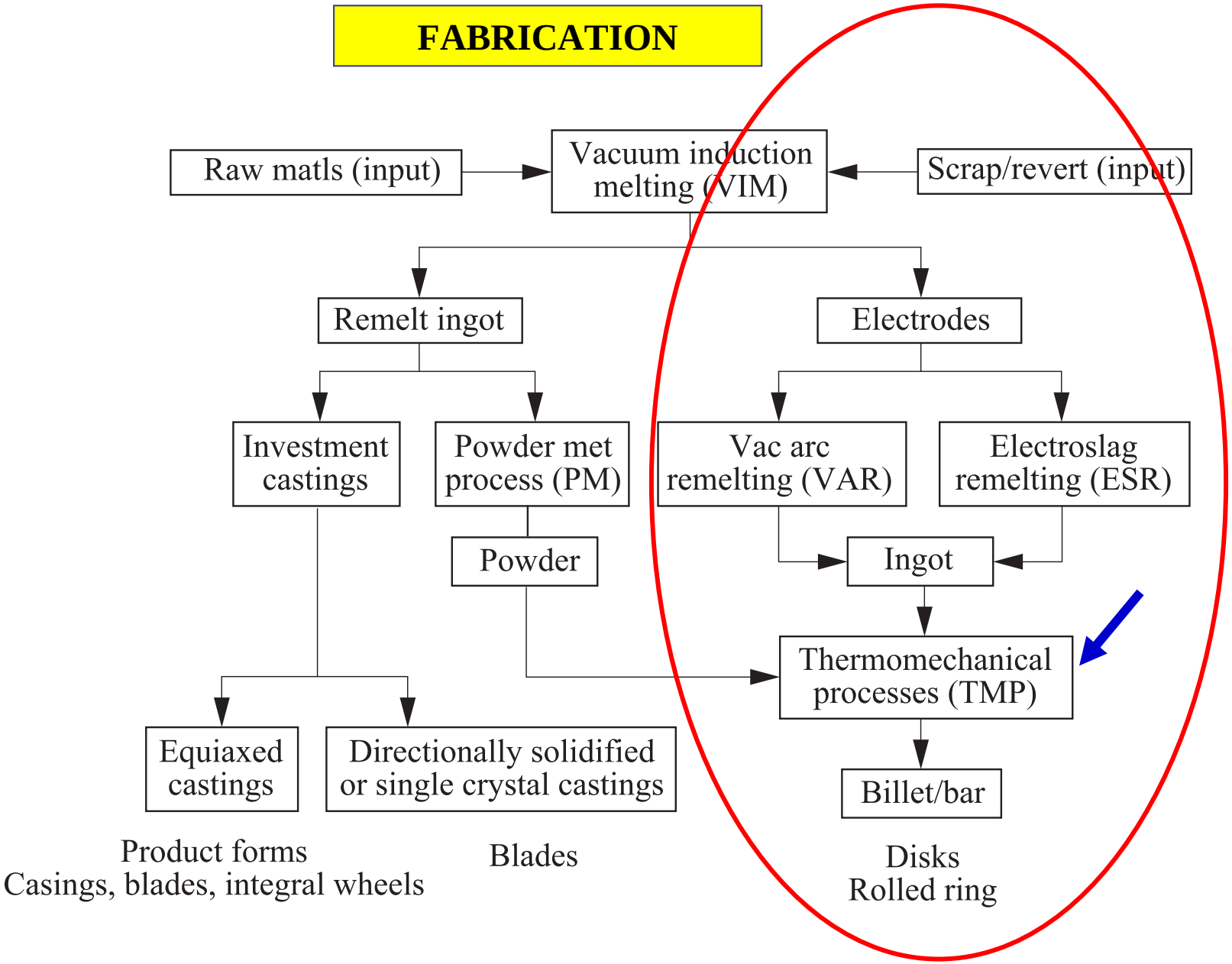
Ni BASED SUPERALLOYS

	Element (wt. %)																
	Ni	Fe	Co	Cr	Mo	W	Ta	Nb	Al	Ti	V	C	B	Zr	Hf	Y	Re
Product Form/Alloy																	
CAST/WROUGHT																	
IN-718	50	30		18	3			5.2	0.6	0.8		0.05	0.006				
Waspaloy	58		13	19	4.3				1.3	3		0.08	0.006	0.06			
INVESTMENT CAST																	
Rene 77	58		15	15	4.2				4.3	3.3		0.07	0.015	0.04			
Rene 80	60		9.5	14	4	4			3	5		0.17		0.03	0.8		
POWDER METALLURGY																	
Rene 95	Bal		8.1	12.8	3.6	3.6		3.6	3.6	2.6		0.08	0.01	0.053			
N18	Bal		15.5	11.5	6.5				4.3	4.3		0.02	0.015		0.5		
IN-100	Bal		18.5	12.4	3.2				5	4.3	0.8	0.07	0.02	0.06			
Udimet 720	Bal		14.7	16	3	1.25			2	5		0.025	0.02	0.03			
CAST SINGLE CRYSTAL																	
CMSX - 2	66		4.6	8	0.6	7.9	5.8		5.6	0.9		0.005					
CMSX-4	Bal		9	6	0.6	6	7		5.6	1					0.1		3
Rene N4	63		7.5	9.2	1.6	6	4	0.5	3.77	4.25							
PWA 1480	63		5	10		4	12		5	1.5							
PWA 1493*	Bal		4.9	9		3.8	5		3.6	1		0.02	0.03	0.07		0.02	
* Mo+Ta+W = or > 10%																	

See also Alloys 625 & 706

FABRICATION



A SHORT HISTORY OF INCONEL 718

1950 | 1960 | 1970 | 1980 | 1990 | 2000 | 2010

1959 : H. Eiselstein Huntington Alloy Products
Nb addition to avoid Strainage Cracking

1965 : Selection as the material for GE's new family of engines

1970 : Approved as turbine material

Early 80's : Alloy 718 became the most important superalloy (Cobalt supply crisis)

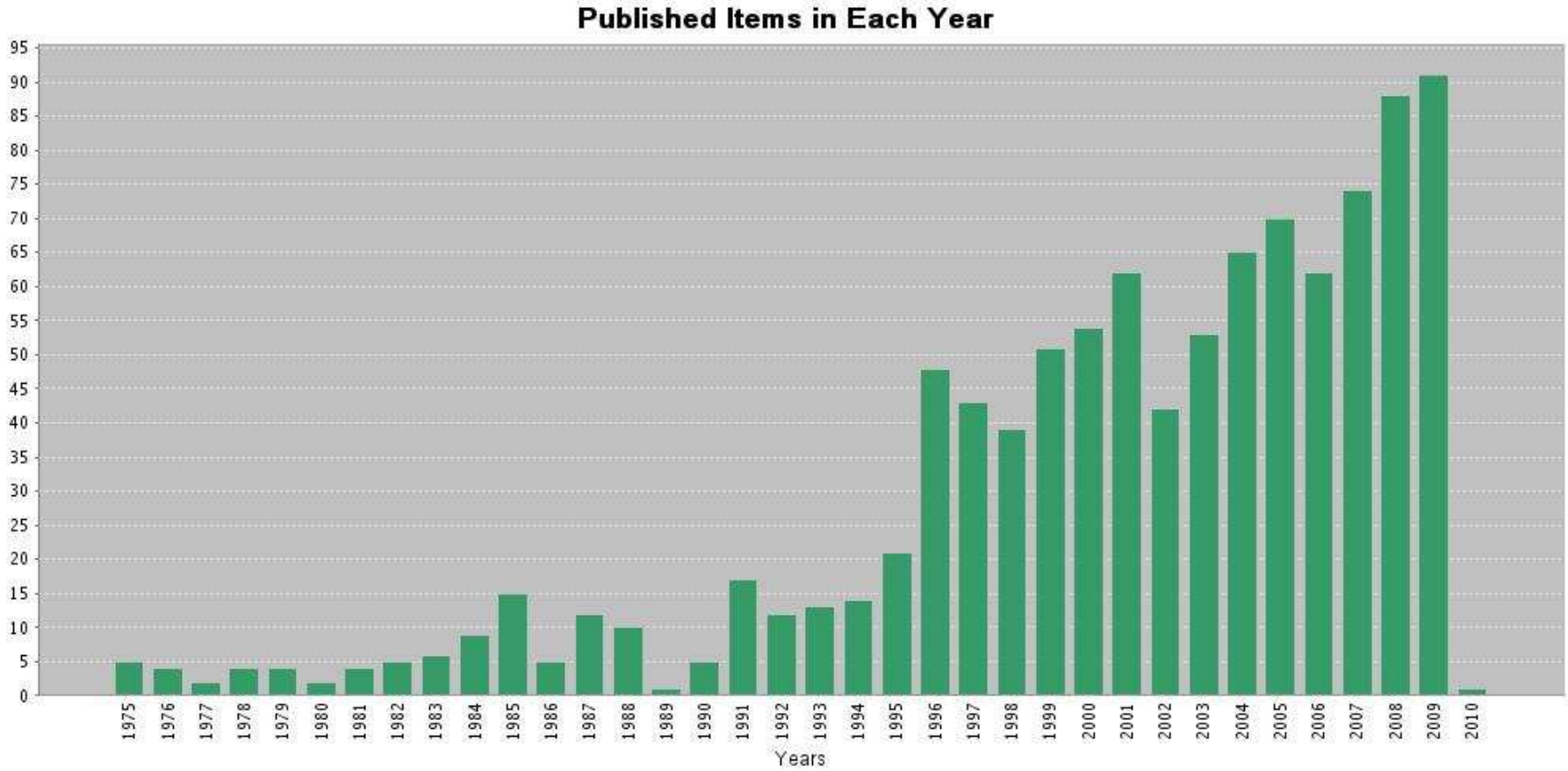
> 2000 : WP ~10.000 T/Year
15 € / Kg

ALLOY 718 & OTHER γ'' STRENGTHENED ALLOYS (Wt. %) (— At. %)

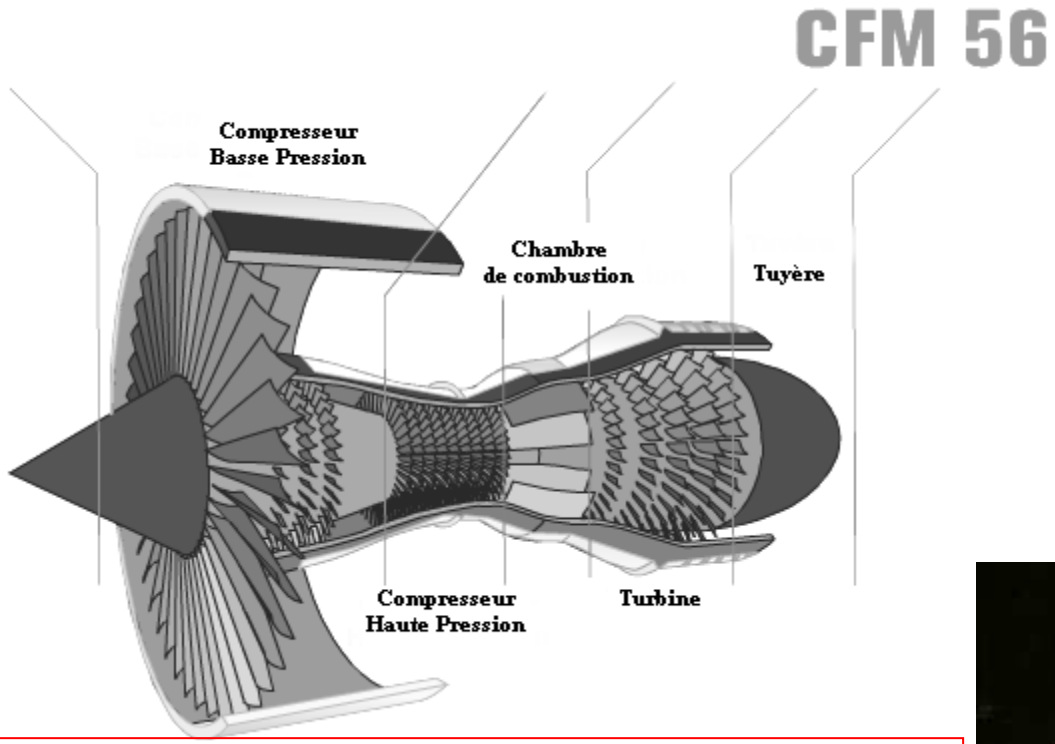
Alloy	C	Cr	Ni	Nb	Ti	Al	Mo	Fe	Ti+Al+Nb	(Ti+Al)/Nb
718	0.04	19	53	5.1	0.90	0.50	3	18.5	6.50 5.30	0.27 0.70
725	0.02	20	55.5	3.40	1.30	0.20	7.50	10.6	4.90	0.44
706	0.03	17.5	37	2.50	2.10	0.40		40.5	5 4.30	0.50 1.40
DT 706	0.03	18	55	2.90	1.90	0.55		22	5.35 5.20	0.85 1.90
625	0.05	22	58	3.70	0.40	0.40	9		4.50	0.215

ISI WEB OF KNOWLEDGE

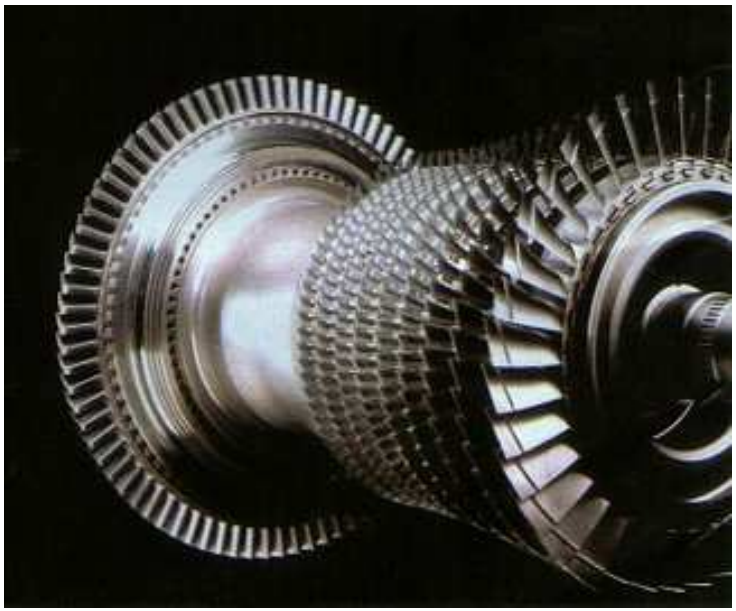
Number of Publications per Year - Inconel 718



APPLICATIONS OF INCONEL 718



Turbine Discs



Other Applications :

- Nuclear Industry : Springs for internals
- Rockets: Liquid H_2 & O_2 pumps

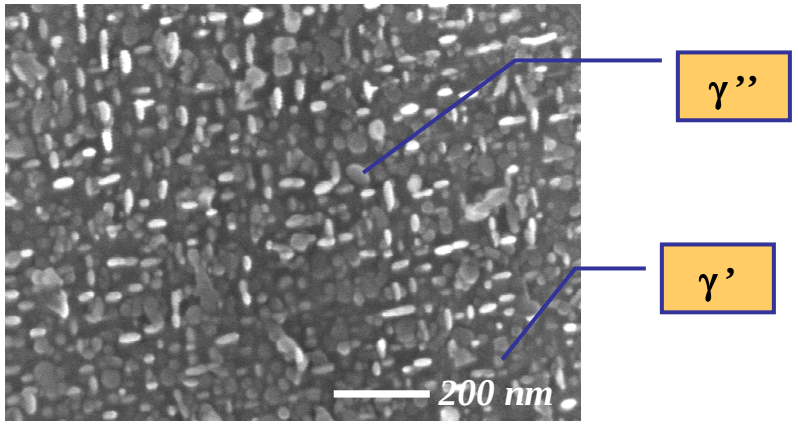
Production ~ 10.000 T/year
(most widely used Superalloy)
Cheap alloy ~ 15 € / Kg

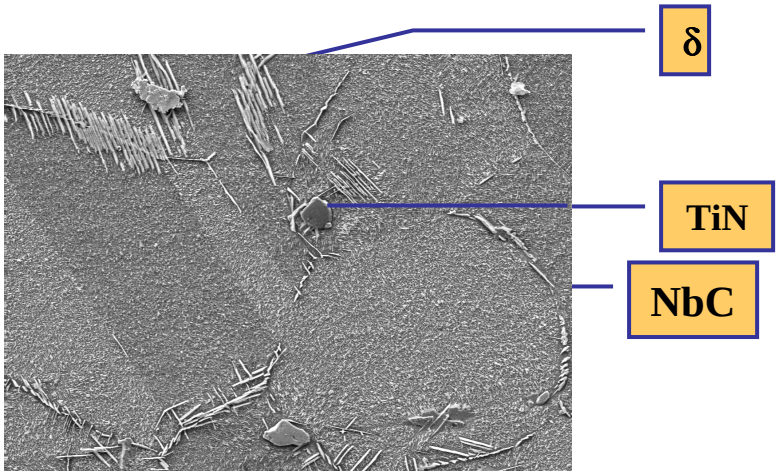
OTHER PHASES IN INCONEL 718

F. Alexandre, PhD Thesis 2004

Inconel 718 (Wt %)

Elément %	Ni	C	Cr	Fe	Nb	Mo	Ti	Al
Mini	Base	0.02	17.00	15.00	**4.75**	2.80	0.75	0.30
Max	Base	0.08	21.00	21.00	**5.50**	3.30	1.15	0.70





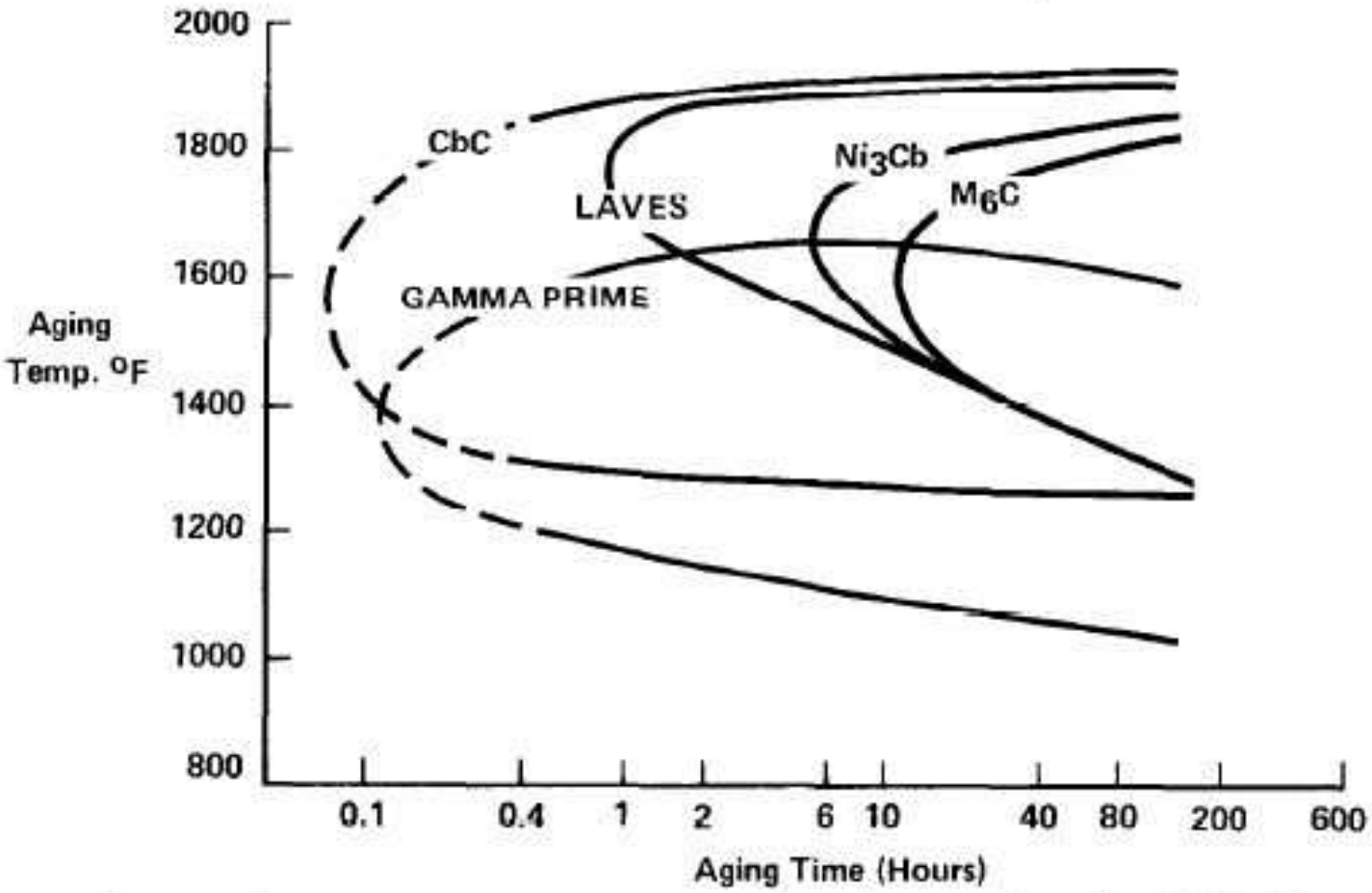
718TR : **Annealing : 955°C-1h;**

Ageing : 720°C/8h + 620°C/8h

718DA : **Directly aged after forging**

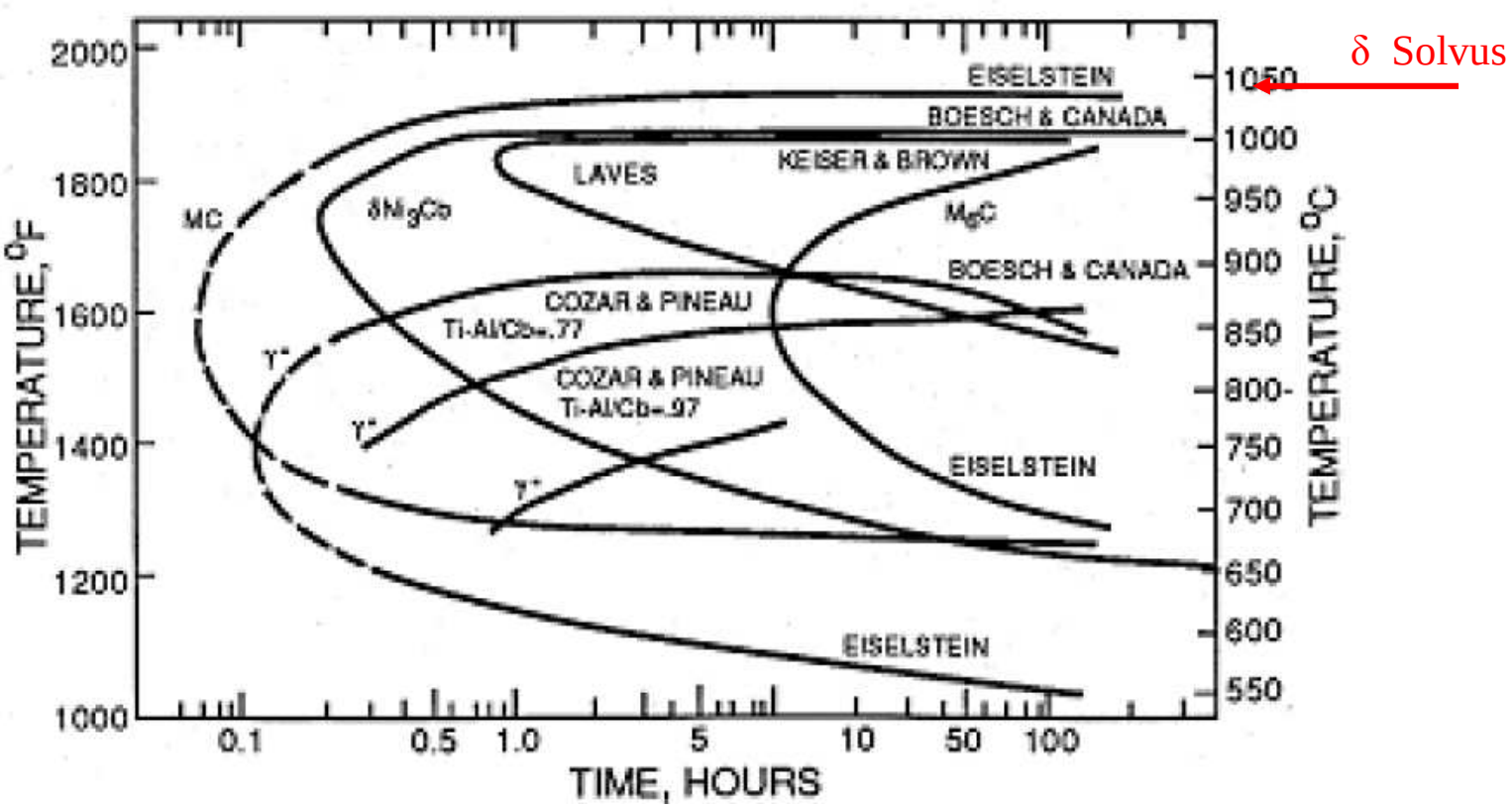
TTT DIAGRAM FOR INCONEL 718

A. Lingenfelter, Superalloy 718, Metallurgy & Applications, TMS, 1989, p. 673



Solution- Annealed at 2100°F (1150°C)- 1 Hr- W.Q.

TTT DIAGRAM FOR INCONEL 718



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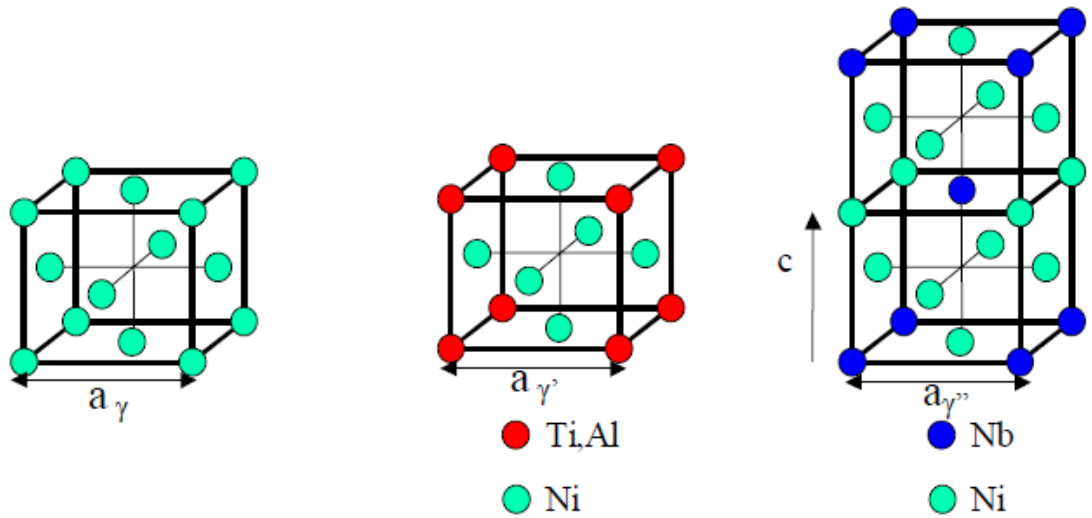
A_3B PRECIPITATES IN INCONEL 718 (4)

Elements %	Ni	C	Cr	Fe	Nb	Mo	Ti	Al
Mini	Base	0.02	17.00	15.00	**4.75**	2.80	0.75	0.30
Maxi	Base	0.08	21.00	21.00	**5.50**	3.30	1.15	0.70

IN 718 – Composition (Wt %)



γ (CFC)

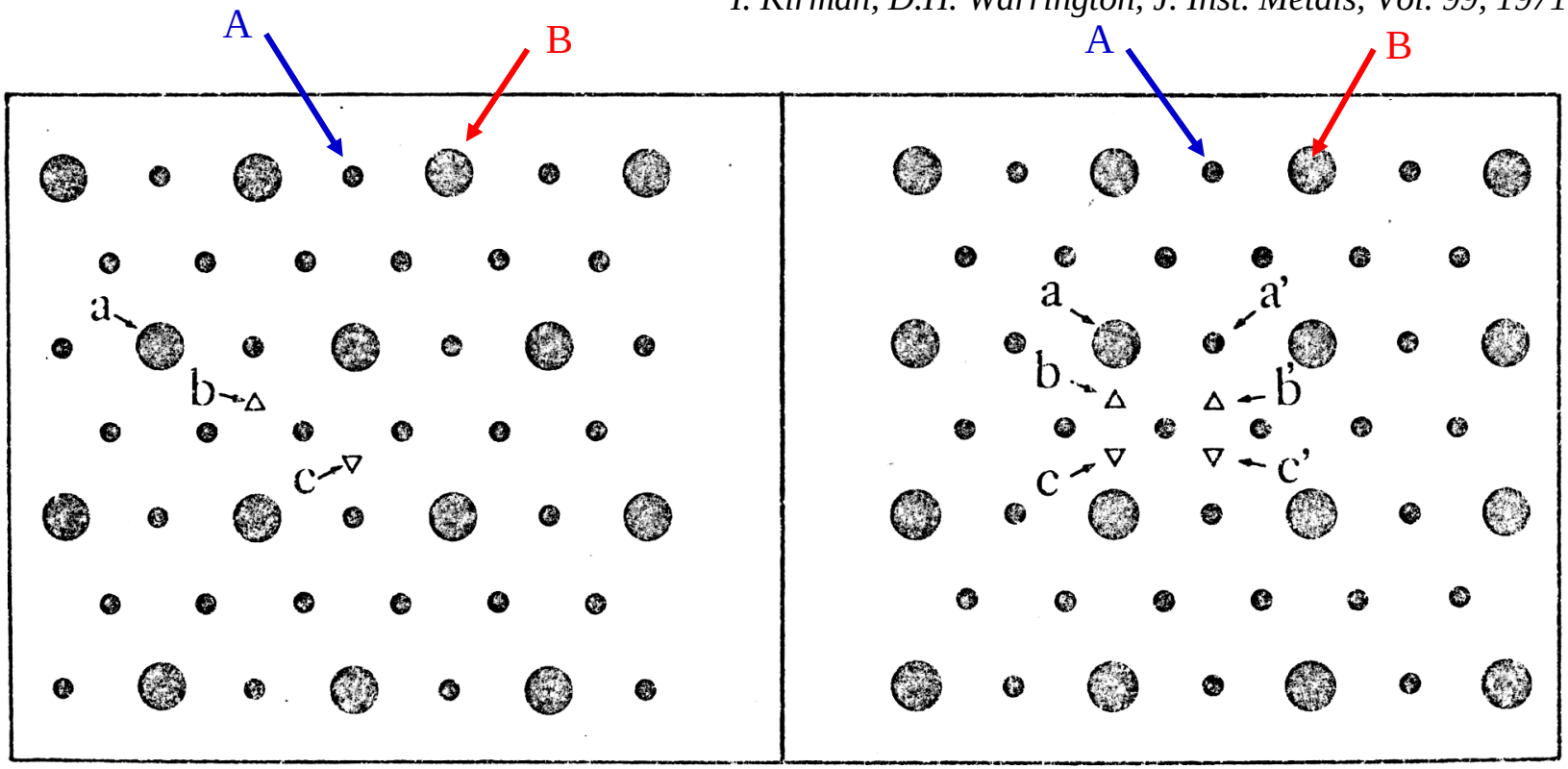
γ'(Ni_3(Ti,Al) ; $L1_2$) ~200Å

γ ''(Ni_3(Nb) ; DO_{22}) 15% ~200Å

Strengthening precipitates in IN 718

A_3B PRECIPITATES (1)

R. Cozar, A. Pineau, Met. Trans., Vol. 4, 1973, p. 47
D.F. Paulonis et al., Trans. ASME, Vol. 62, 1969, p. 611
I. Kirman, D.H. Warrington, J. Inst. Metals, Vol. 99, 1971, p. 197



Planes T Planes R

Close Packed Planes in A_3B compounds – Type T or R
Large Symbols : Atoms B; Small Symbols : Atoms A
a, b, c, a', b', c' planar projection of atoms B on successive closed packed planes

A_3B PRECIPITATES (2)

	γ'			γ''		δ , β
	Planes Type T			**Planes Type R**		
Phases	Cu_3Au	Ni_3Ti	Ni_3Sn	Al_3Ti	β – Pt_3Nb	β – Cu_3Ti
Base Ni	Ni_3Al	Ni_3Ti	Ni_3Sn	Ni_3V	Ni_3Ta	Ni_3Nb
Bravais Lattice	Cubic	Hexagonal	Hexagonal	BCT	Orthorhombic	Orthorhombic
Spatial Group	P m3m	P 6_3 / mmc	P 6_3 / mmc	I 4 / mm	P 2_1 / m	P mm
Struktur Berich	L 1_2	DO_{24}	DO_{19}	DO_{22}	?	DO_a
Parameters (nm) (Ni base alloys)	0.3567	a = 0.5093 c = 0.8276 c/a = 1.625	a = 0.5293 b = 0.4244 c/a = 0.802	a = 0.3542 b = 0.7173 c/a = 2.025	a = 0.5126 b = 2.537 c = 0.4523 α = 90° 50	a = 0.5106 b = 0.4251 c = 0.4556
Compact Plane	(111)	(0001)	(0001)	(112)	(010)	(010)
Zhdanov Notations	1 <u>0</u> T	2 <u>2</u> T	1 <u>1</u> T	1 <u>0</u> R	3 <u>1</u> R	1 <u>1</u> R

Structures A_3B with T or R Type

SIZE and ELECTRONIC CONCENTRATION EFFECTS (3)

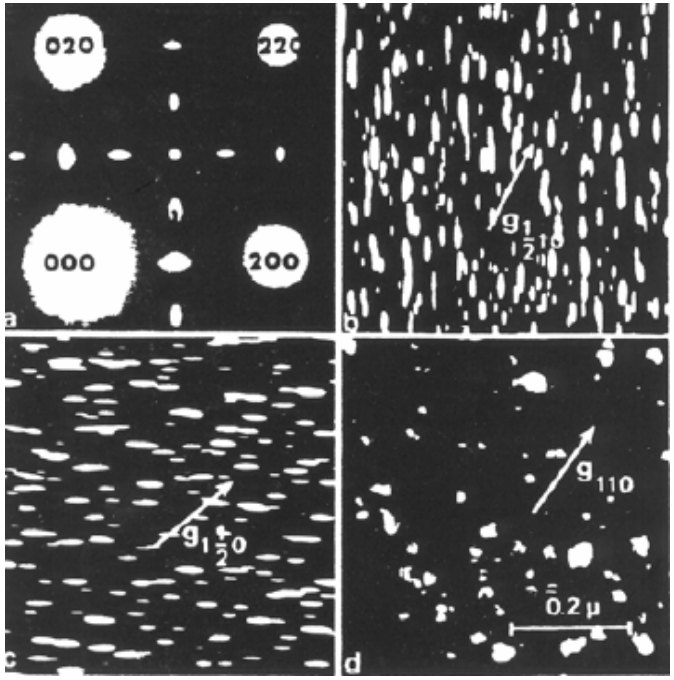
J.H.N. Van Vucht et al., J. Less-Com.Metals, vol.10, 1966, p. 98
J.H.N. Van Vucht et al., J. Less-Com.Metals, vol.11,1966, p. 308
A.K. Sinha, Trans. AIME, vol. 245, 1969, p. 237
A.K. Sinha, Trans. AIME, vol. 245, 1969, p. 911
W.T. Geng et al., Physical Review B 76, 2007, pp. 224102.1-22410.2

Composition	Structure	e/a	$\bar{R}_B / \bar{R}_A$
Ni_3Al $Ni_3Al_{0.66}Nb_{0.34}$	1 $\underline{0}$ T (C) 1 $\underline{0}$ T (C)	8.25 8.42	1.153 1.164
Ni_3T_i	2 $\underline{2}$ T (H)	8.50	1.169
Ni_3V	1 $\underline{0}$ R (BCT)	8.75	1.097
Ni_3Nb	1 $\underline{1}$ R (O)	8.75	1.185

- Transition between T & R Structures for e/a ~ 8.65
- Smaller influence of $\bar{R}_B / \bar{R}_A$ ratio (which does not change too much in Ni-based alloy !)

γ'' PRECIPITATES IN INCONEL 718 (5)

R. Cozar, A. Pineau, Met. Trans., vol. 4, (1973), pp. 47-59



Lattice Parameters (Alloy 2) (nm)

Condition	a_γ	$a_{\gamma'}$	$a_{\gamma''}$	$c_{\gamma''}$
1200°C - WQ	0.3601			
770°C - 1h	0.3594	0.3607		
750°C – 524 h	0.3594	0.3605	0.3626	0.7416

$$\frac{a_{\gamma'} - a_\gamma}{a_\gamma} = 0.36\%$$

$$\frac{(c/2_{\gamma''} - a_\gamma)}{a_\gamma} = 3.17\%$$

$$\frac{(c/2_{\gamma''} - a_{\gamma'})}{a_{\gamma'}} = 2.86\%$$

$$\frac{a_{\gamma''} - a_\gamma}{a_{\gamma'}} = 0.89\%$$

$$\frac{a_{\gamma''} - a_{\gamma'}}{a_{\gamma'}} = 0.58\%$$

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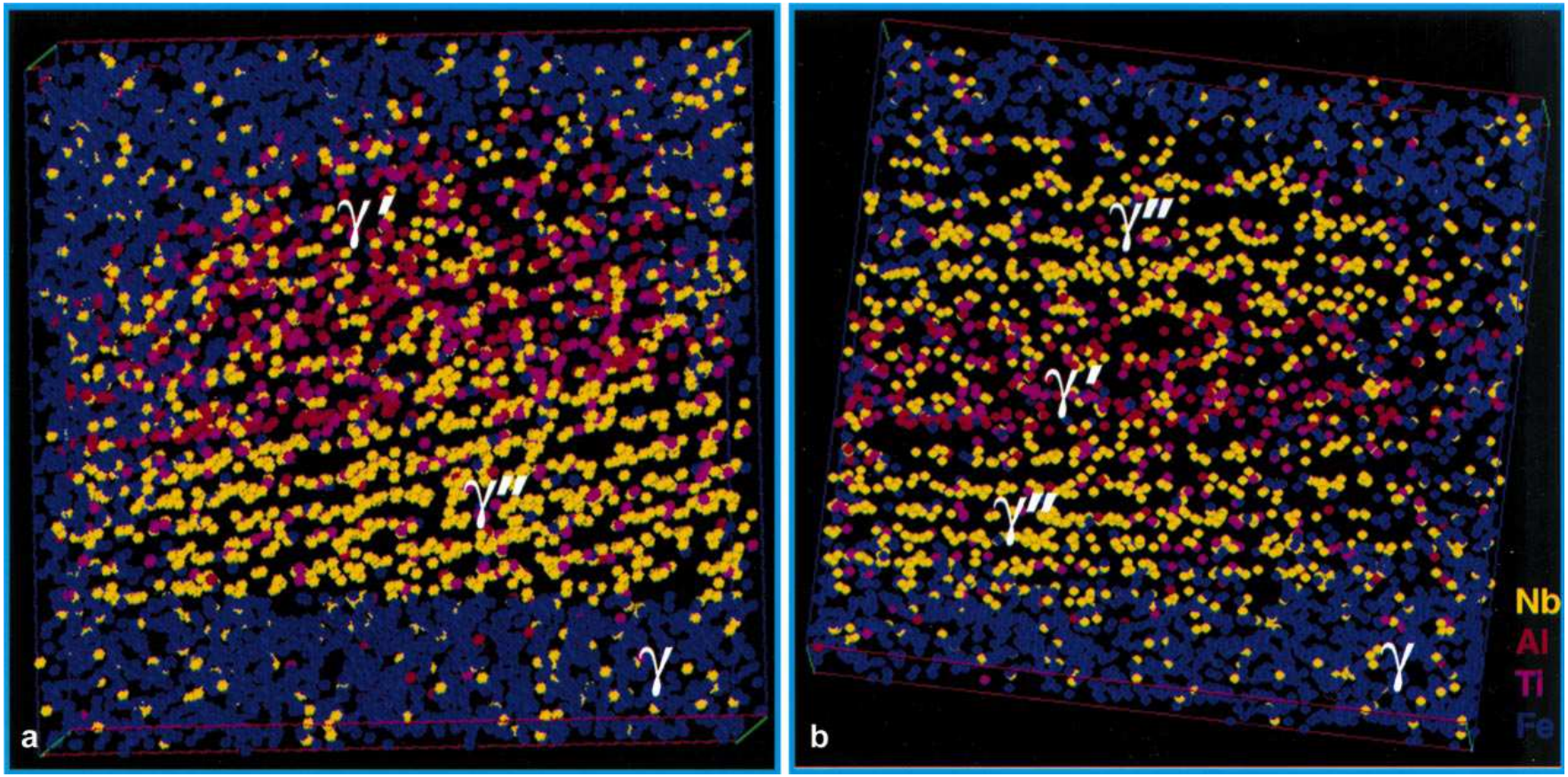
γ' & γ'' COMPOSITION (1)

M.K. Miller, Micron, vol. 32, 2001, pp. 757-764



γ' & γ'' COMPOSITION (2)

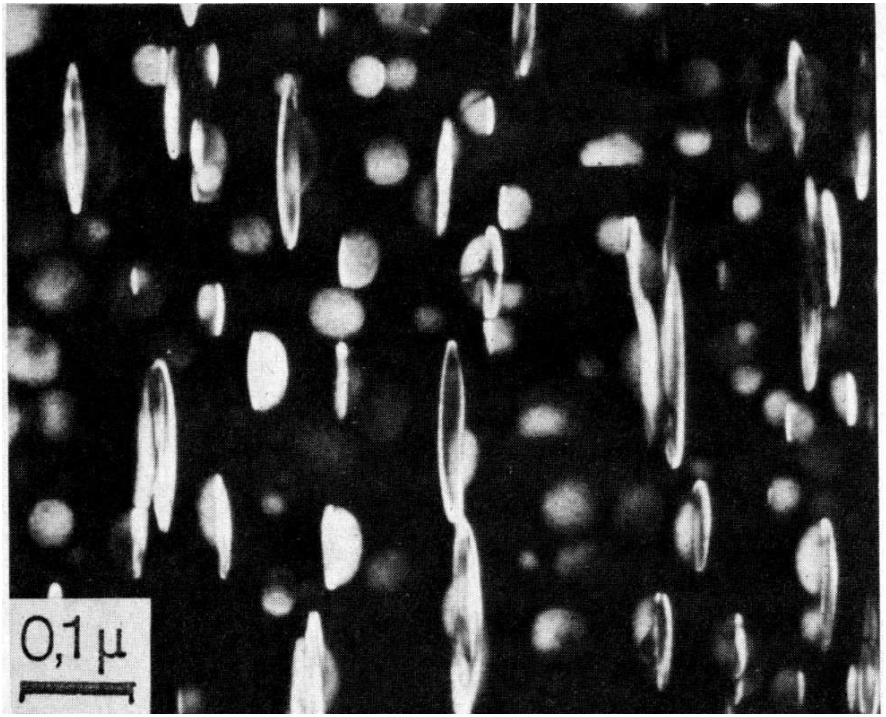
Phase	Heat treatment	Cr	Fe	Nb	Mo	Ti	Al	Co
γ	A + 2012 h at 873 K	27.0	26.2	0.58	2.26	0.19	0.22	0.25
	AC + 2012 h at 873 K	23.8	25.6	0.52	2.54	0.13	0.19	0.38
Primary γ''	AC + 500 h at 873 K	2.00	1.43	16.0	2.38	5.36	0.31	0.39
γ'	A + 2012 h at 873 K	0.33	1.56	8.75	0.31	5.85	10.6	0.21
	AC + 2012 h at 873 K	0.59	1.57	8.21	1.22	3.85	9.28	0.30
γ''	A + 2012 h at 873 K	1.75	1.29	16.6	1.56	3.75	0.43	0.17
	AC + 2012 h at 873 K	1.98	0.81	20.6	2.37	3.68	0.40	0.20

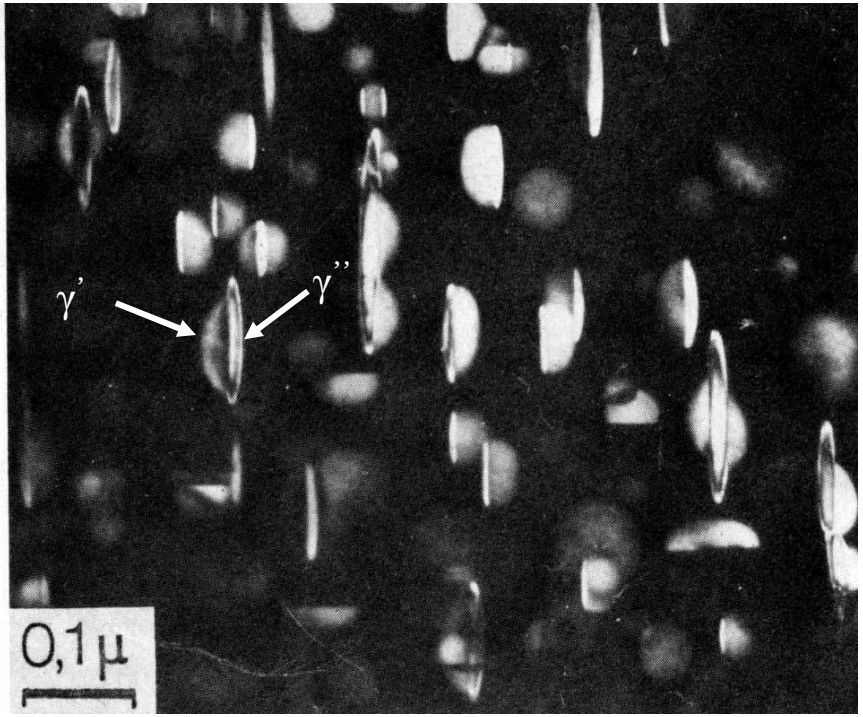
Average Composition of the Phases in Alloy 718 as measured from selected volume analysis of 3D atom probe data. The balance of each analysis is nickel – Data in atomic percent

Note that γ' contains a significant amount of Nb

γ' & γ'' CO-PRECIPITATES IN INCONEL 718 (1)

R. Cozar, A. Pineau, Met. Trans., vol. 4, 1973, pp. 47-59





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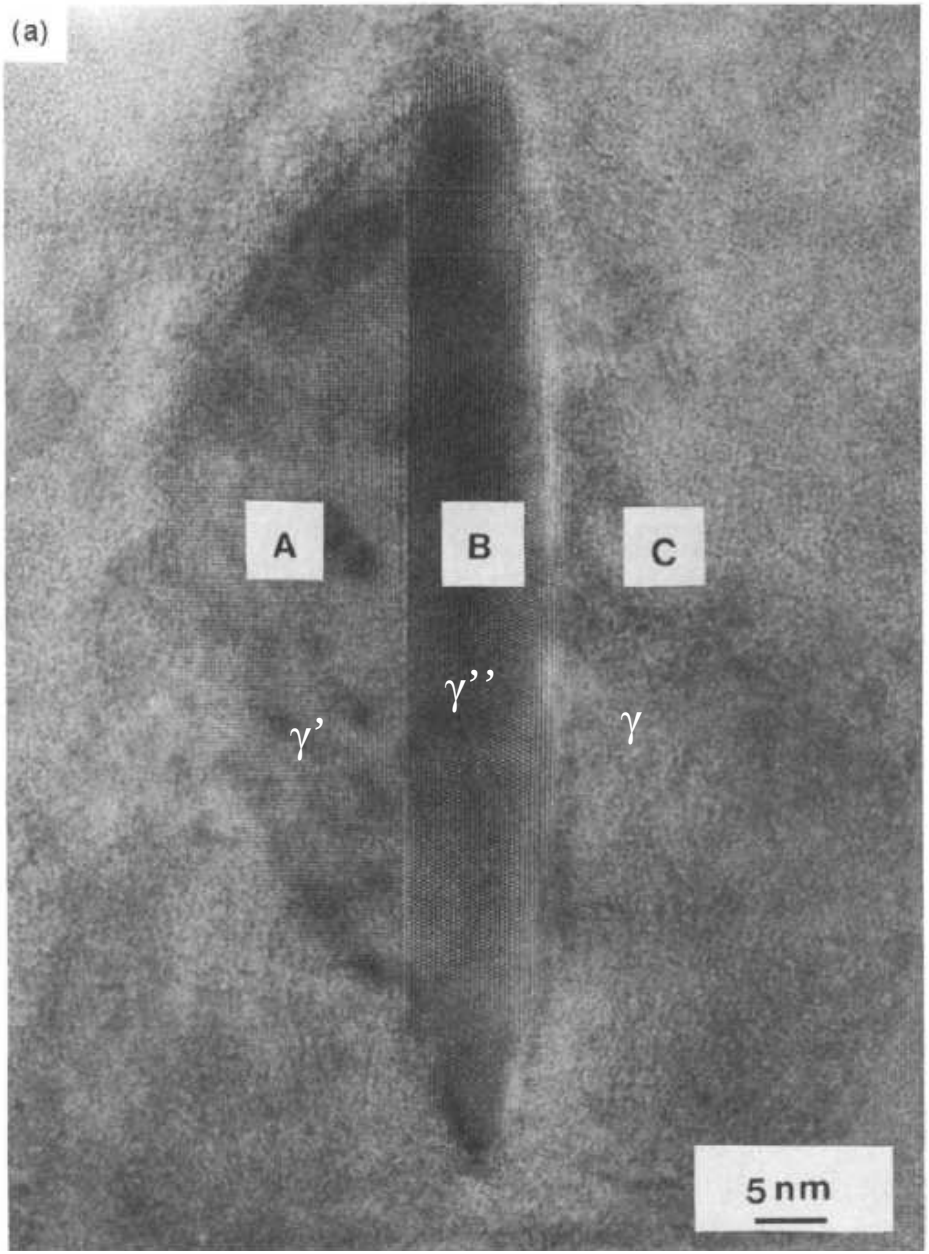
γ' & γ'' CO-PRECIPITATES IN INCONEL 718 (2)



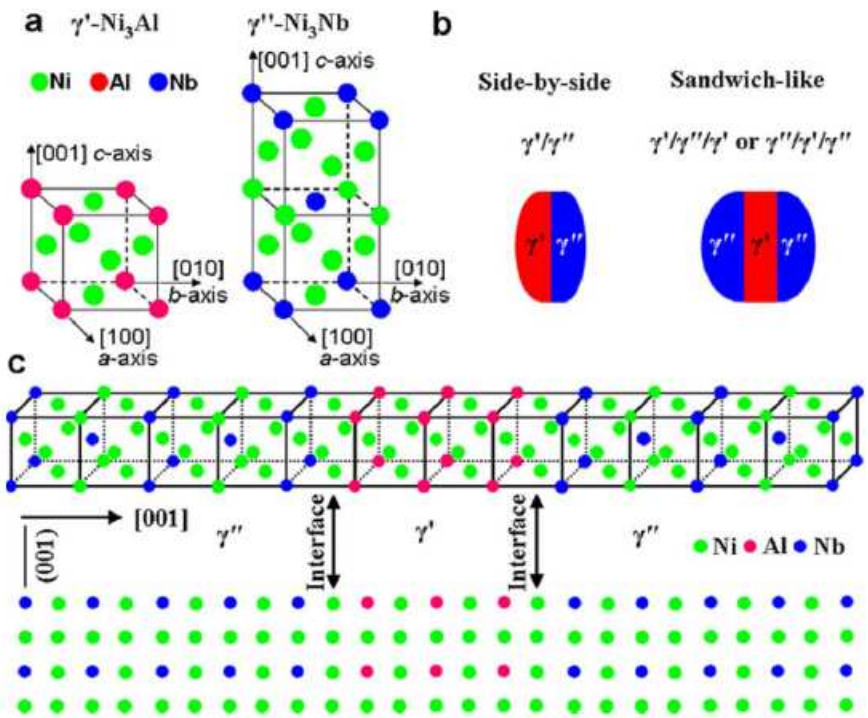
J. He et al., Acta Metall. Mater., vol. 43, (1995), pp. 4403-4409

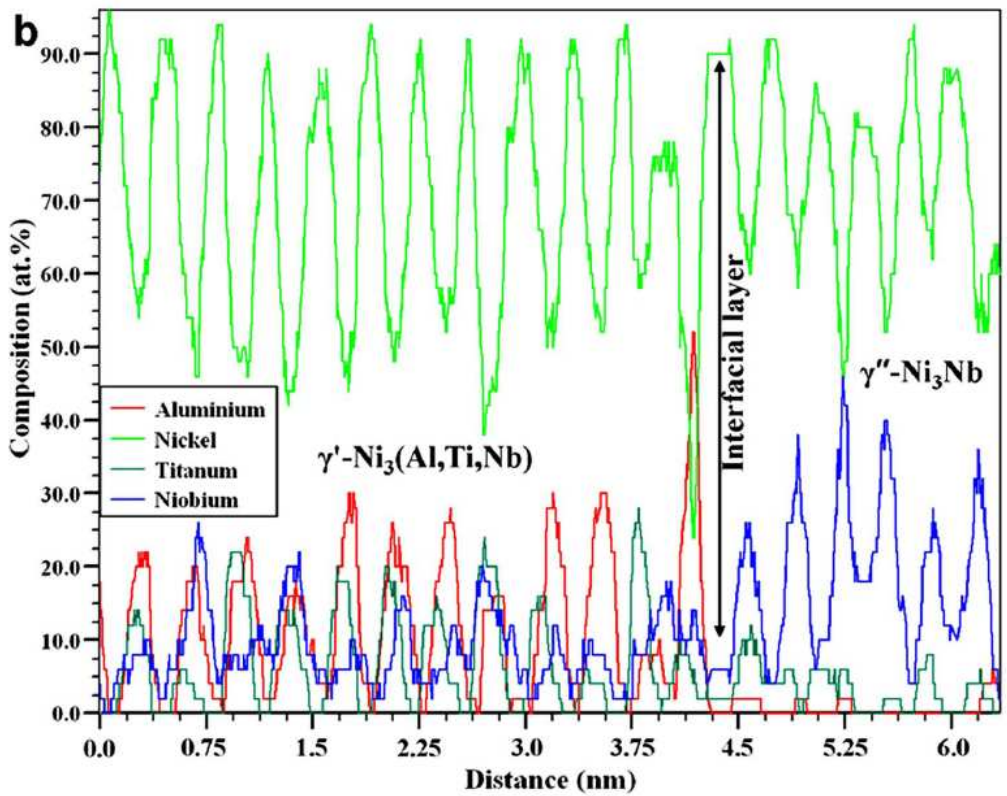
Inconel 718
HREM Micrographs
of γ' /γ'' co-precipitates

γ'/γ'' INTERFACE – COMPOSITION (3)

W.T. Geng et al., Physical Review B76, (2007), 224102

- Density functional theory (DFT)
- 3D atom probe tomography





- $L1_2$ interface structure is 0.66 ev (205 mJ) lower in energy than the DO_{22} structure
- AFM : Segregation of Al atoms in the γ' phase at the γ'/γ'' interface

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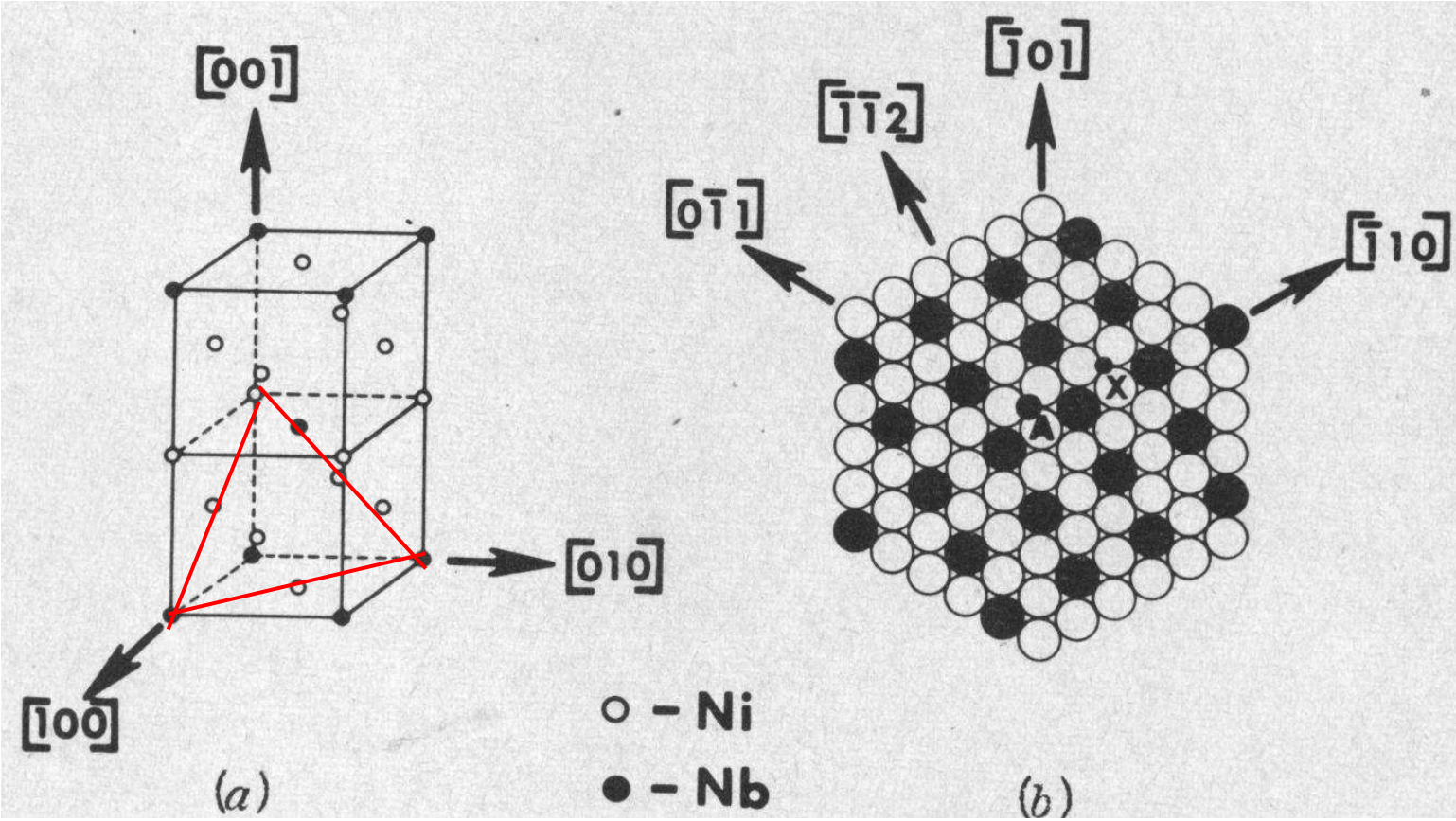
DISLOCATIONS IN γ'' PHASE (1)

J.M. Oblak et al. Met. Trans. Vol. 5, 1974, pp. 143-153



Perfect Dislocations

$\overline{AX} = a[\bar{1}10] = \frac{a}{2}[\bar{1}10] + \frac{a}{2}[\bar{1}10]$ → **Order maintained in γ'' (paired dislocations as in γ')**

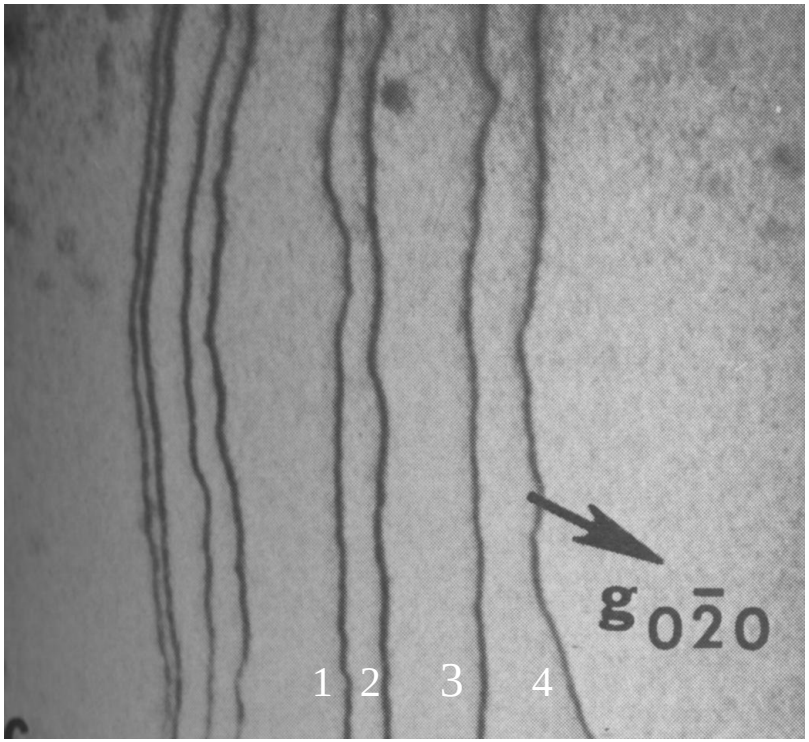
$2 \times \text{"}\overline{AX}\text{" along } [\bar{1}01] \text{ and } [0\bar{1}1]$ **-To keep order in γ''** → **quadruplets of** $\frac{a}{2}<110>$ **dislocations**

Partial Dislocations

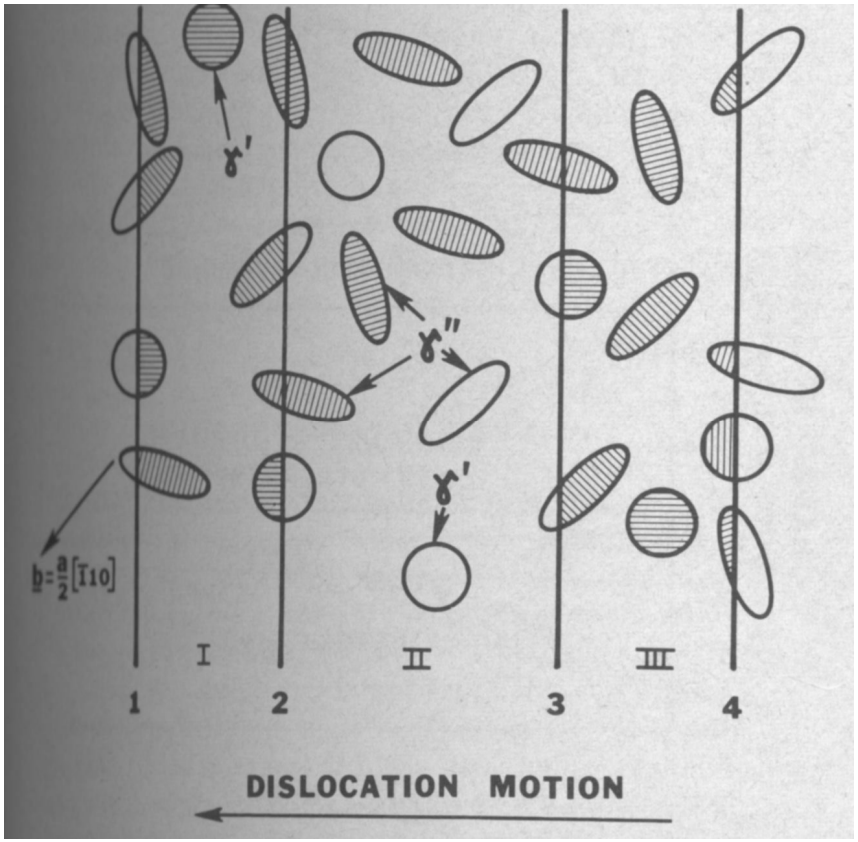
$\frac{a}{6}[\bar{1}\bar{1}2]$ **Transforms DO_{22} abcdef stacking to abab stacking of stable orthorhombic Ni_3Nb phase (DO_{19})**

DISLOCATIONS IN γ'' PHASE (2)

J.M. Oblak et al. Met. Trans., Vol. 5, (1974), pp. 143-153



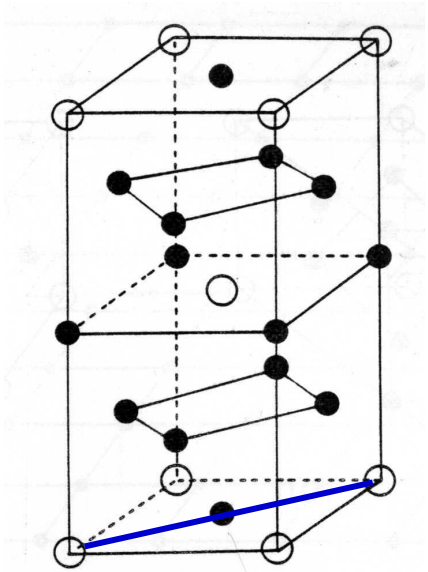
O.2 µm



APB Energy ~ 300 mJ / m^2

DISLOCATIONS IN γ'' PHASE (3)

D. Fournier, PhD Thesis, 1977



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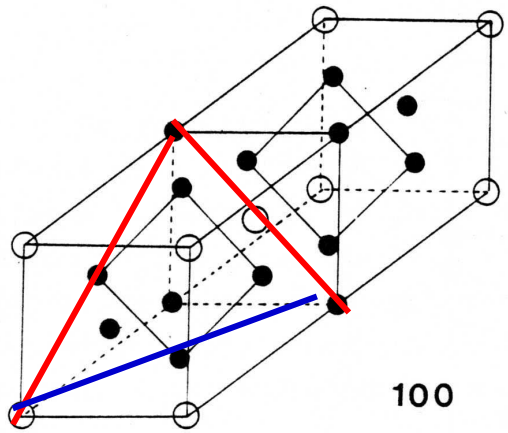

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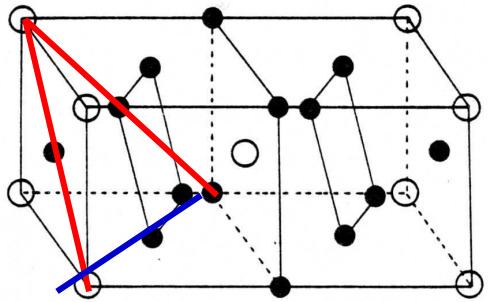
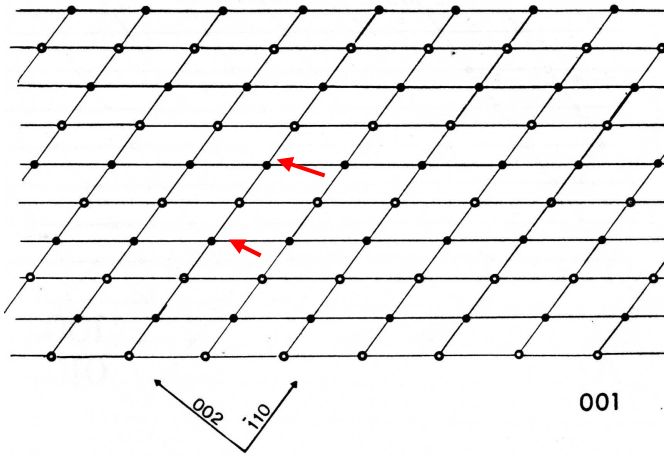


010



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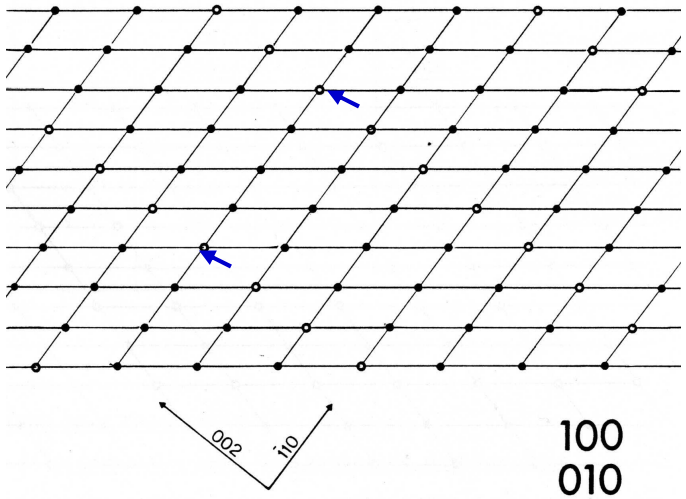


100
010

PARTIAL DISLOCATIONS IN γ'' PHASE (4)

D. Fournier, PhD Thesis, 1977

Stacking faults in γ'' phase every plane

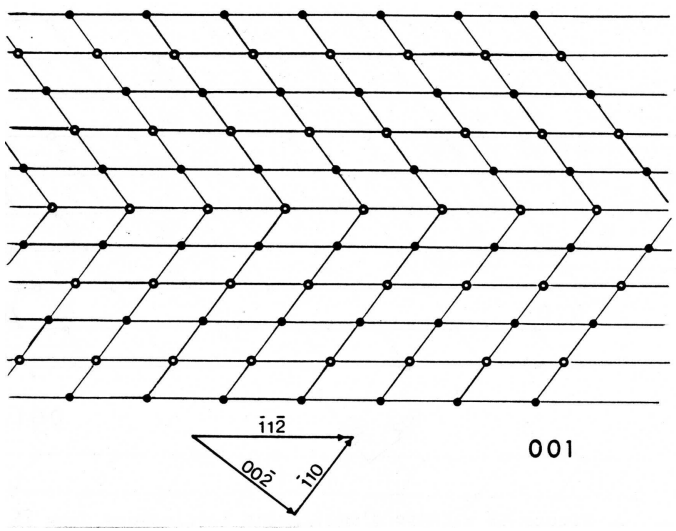
ABCA'B'C'
ABCA'CA'B'C'
ABCA'CBCA'B'C'
ABCA'CBABCA'B'C'

TWIN

Stacking faults in γ'' phase every two planes

ABCA'B'C'
ABCA'CA'B'C'
ABCA'CA'CA'B'C'
ABCA'CA'CA'CA'B'C'

γ'' ⟶ β (orthorhombic)



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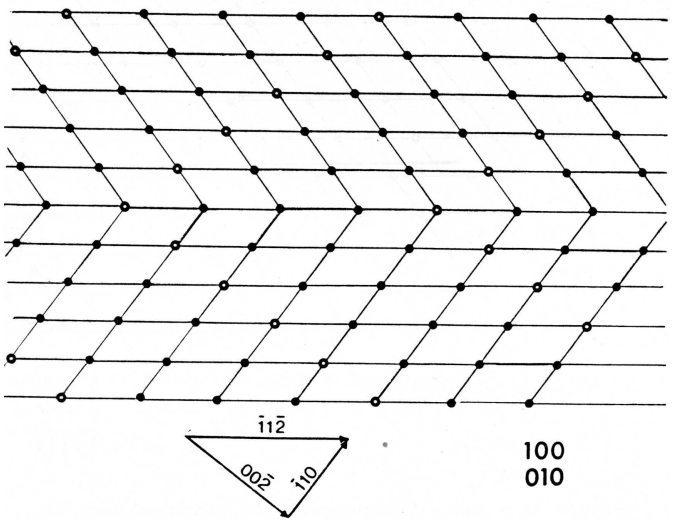
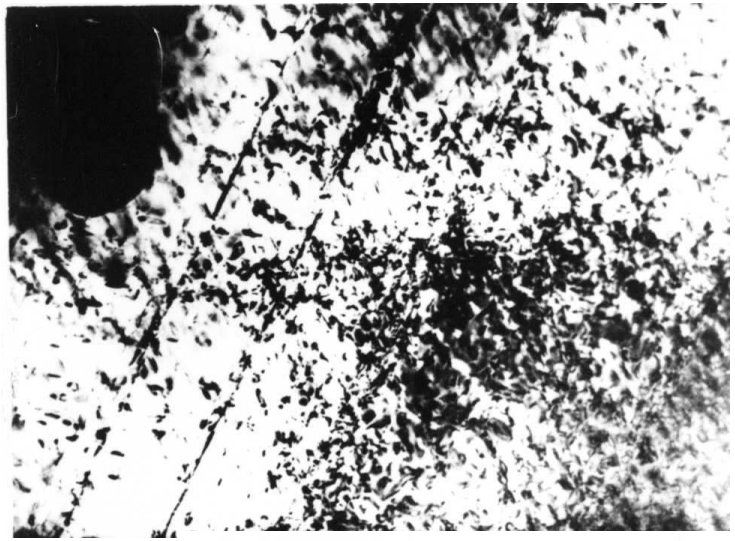


c // <100> or <010>

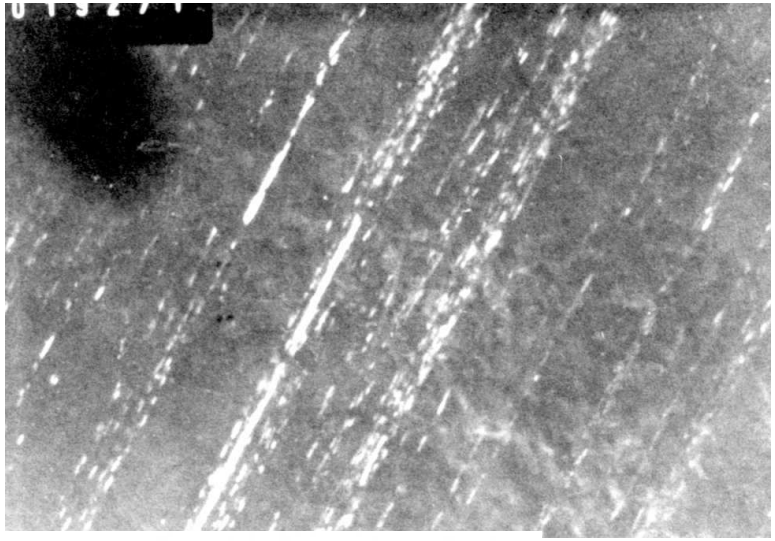
DISLOCATIONS IN γ'' PHASE (4)

M. Clavel, PhD Thesis, 1980

a)



b)



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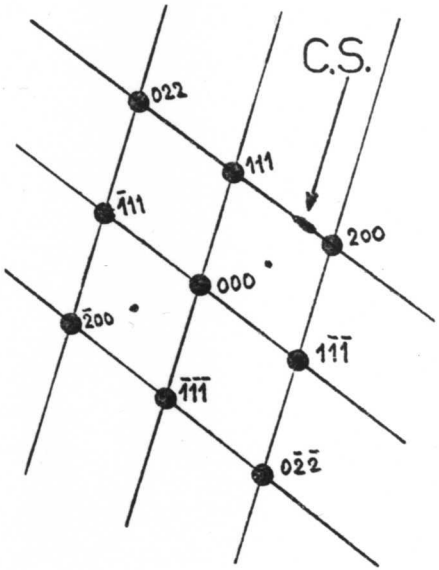

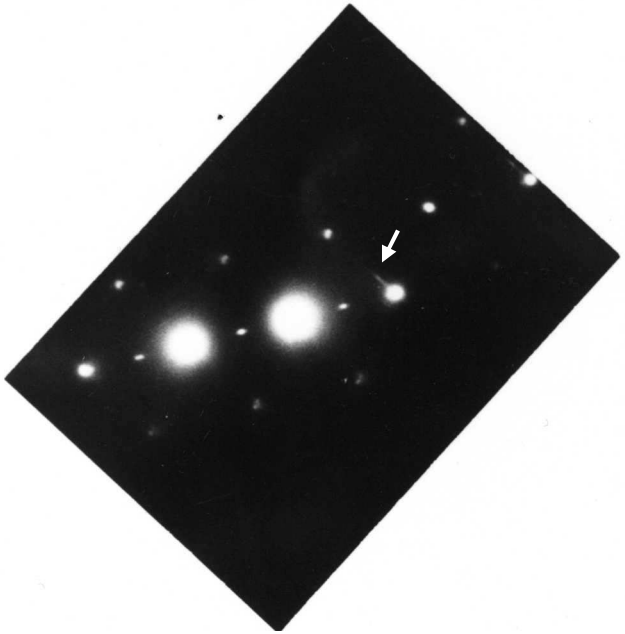

Inconel 718 – 3% Tensile Deformation at 25°C- a) Bright Field ;b) Dark Field; c) Diffraction Pattern

USING STRAIN – INDUCED β NUCLEATION TO MEASURE FATIGUE PLASTIC ZONE SIZE IN INCONEL 718

M. Clavel et al., Met; Trans; , vol.6A, 1975, p. 2305

FRACTURE SURFACE

PLASTIC ZONE SIZE

SEM observation- Mid-plane section of a SEN specimen fatigued at $\Delta K = 55$ MPa $m^{1/2}$ (Rp = 240 µm)

Extent of the monotonic plastic zone revealed by trangralular precipitation of β platelets

Aging at 770°C for 80 hours

ALLOY 718 and OTHER DERIVATIVES BASED ON γ'' PRECIPITATION

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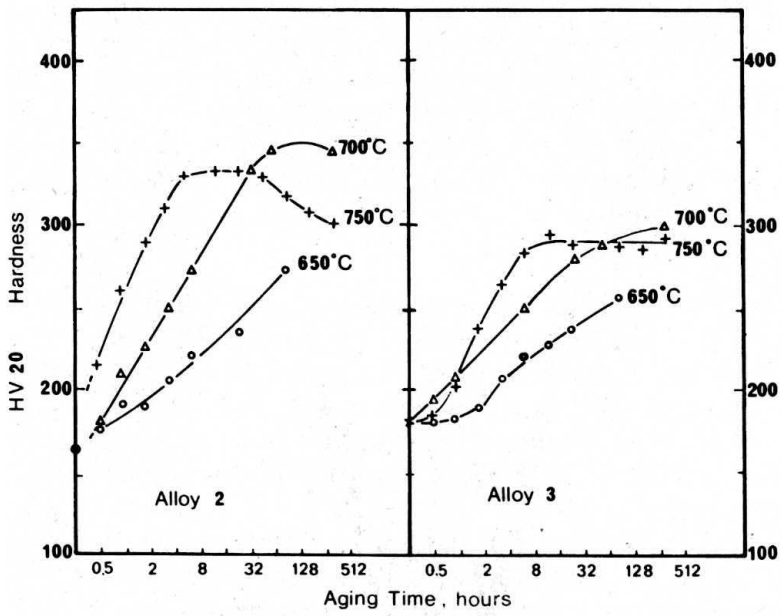
- Crack Initiation : Grain Size and Initiation from Carbide Particles

V. CONCLUSIONS & PROSPECTS

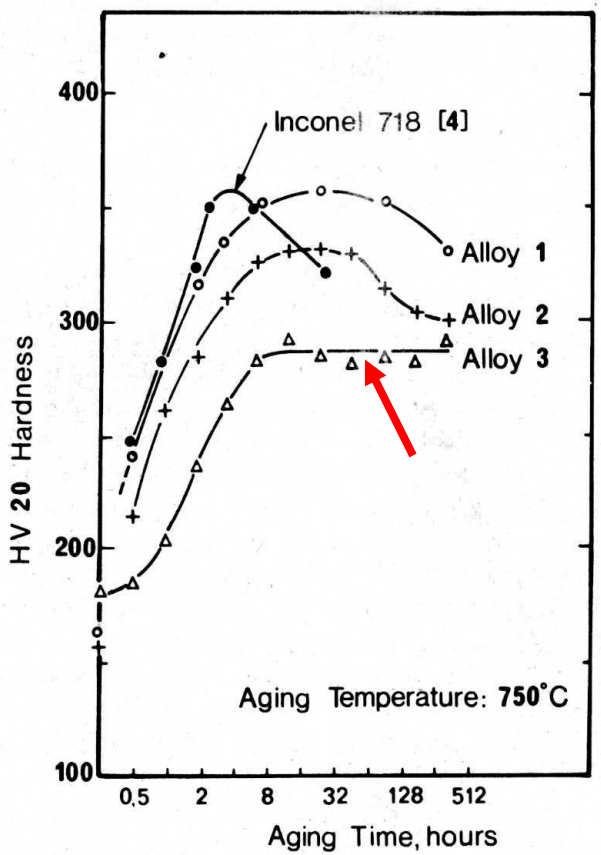
COMPACT MORPHOLOGY

R. Cozar, A. Pineau, Met. Trans., vol. 4, (1973), pp. 47-59

Alloy	Ni	Cr	Fe	Mo	Ti	Al	Nb	(Ti+Al)/Nb	Ti+Al+Nb
Inconel 718	52.4	19	19	3	0.8	0.6	5.2	0.69	5.51
1	52.51	18.16	19.5	2.96	0.82	0.70	5.18	0.77	5.74
2	51.98	18.59	21	2.85	0.72	0.63	3.99	0.89	4.71
3	51.98	18.97	17	7.03	0.59	0.63	3.41	0.97	4.24
4	52.09	18.90	16.4	7.00	0.90	0.74	3.85	1.11	5.14



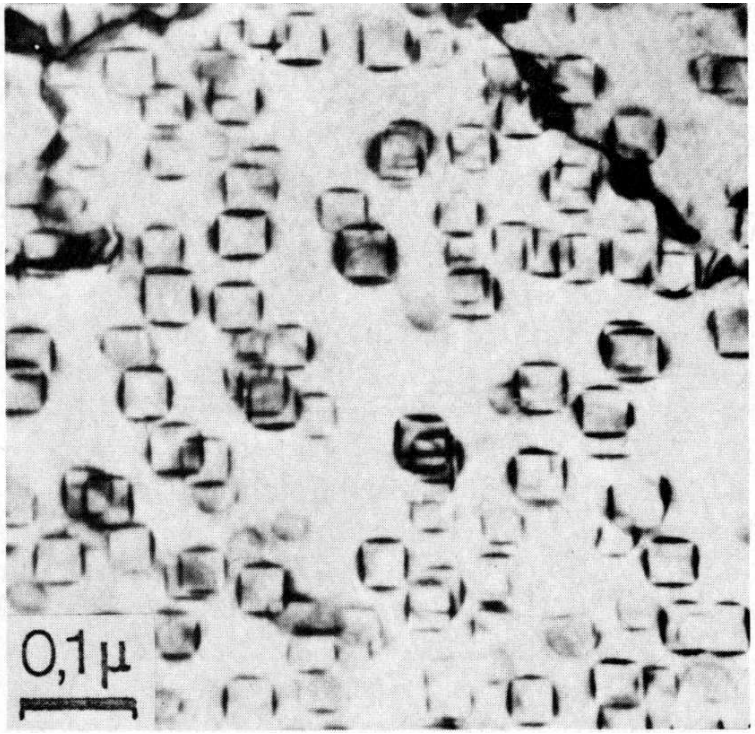
Alloys 2 and 3



Inconel 718 and Alloys 1, 2, 3 aged at 750°C

COMPACT MORPHOLOGY

a)



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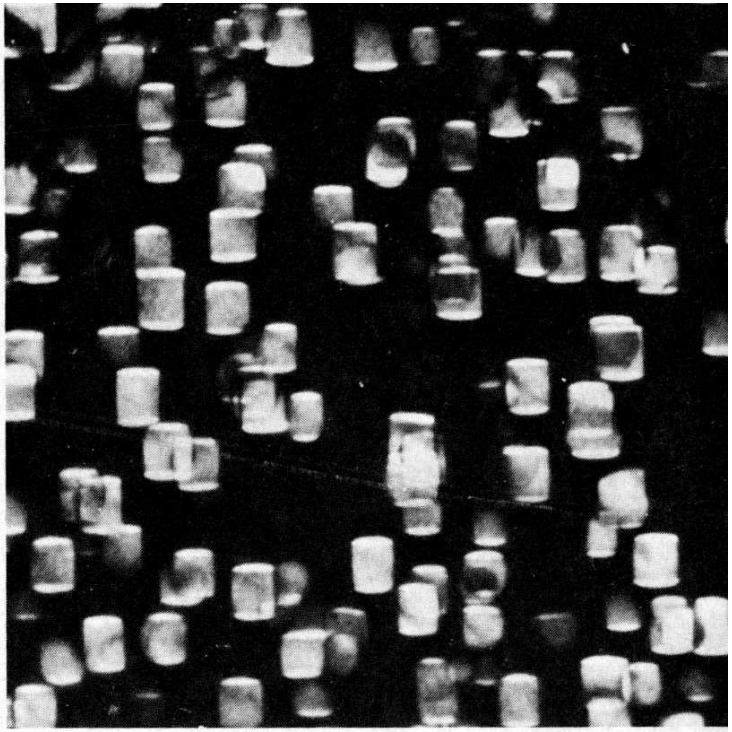
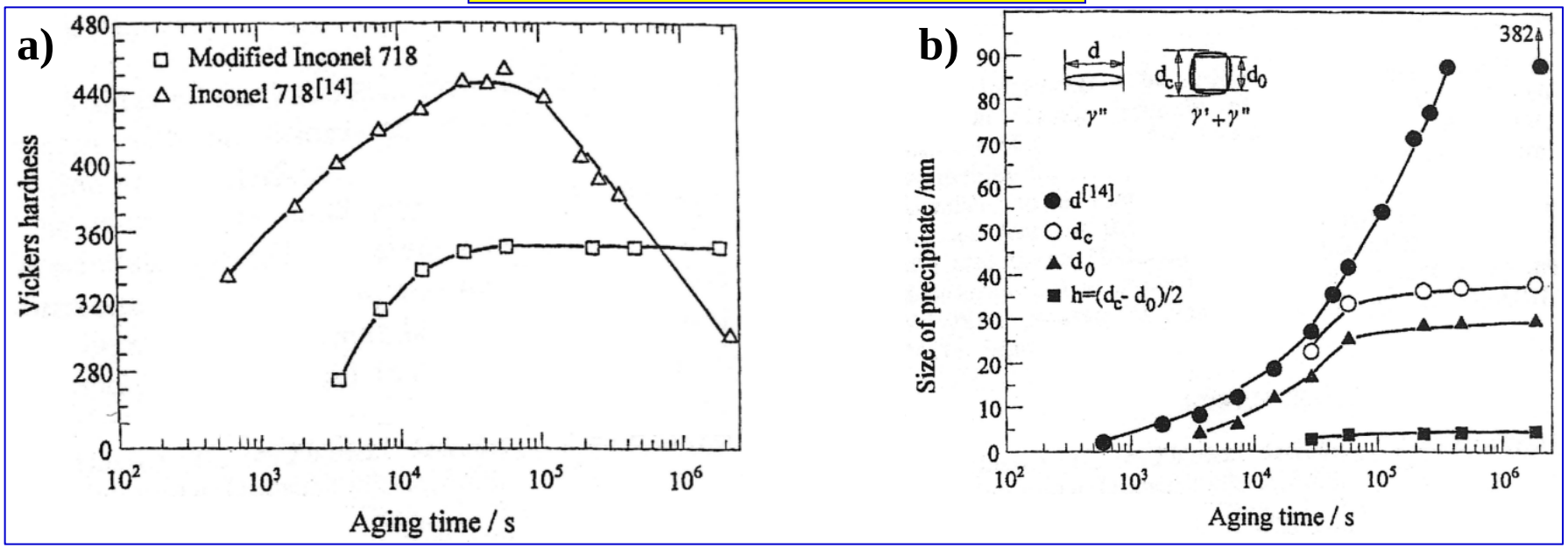
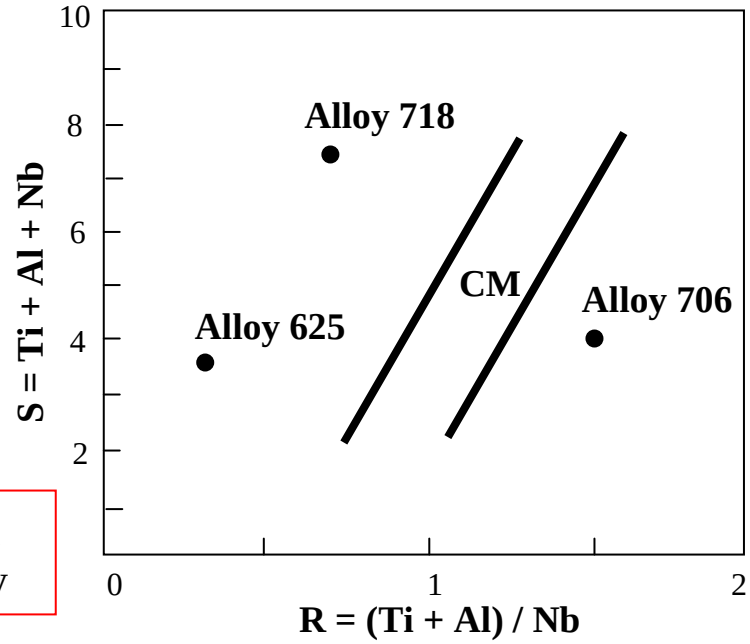


Alloy 3 aged at 750°C for 64 hours – a) Bright field, b) Dark field

COMPACT MORPHOLOGY





Dependence of size variation of compact morphology precipitates and hardness with aging time at 750°C

J.He et al, Acta Mater., vol. 46, 1998, pp. 215-223

T. Shibata et al. J. Japan Inst. Metals, Vol.60, 1996, pp. 802-08

Conditions for obtaining the compact morphology

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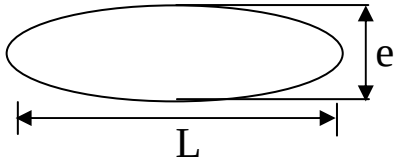
COMPACT MORPHOLOGY

A. Devaux et al., Mat. Sci. Eng., vol.A 486, (2008), pp. 117-122

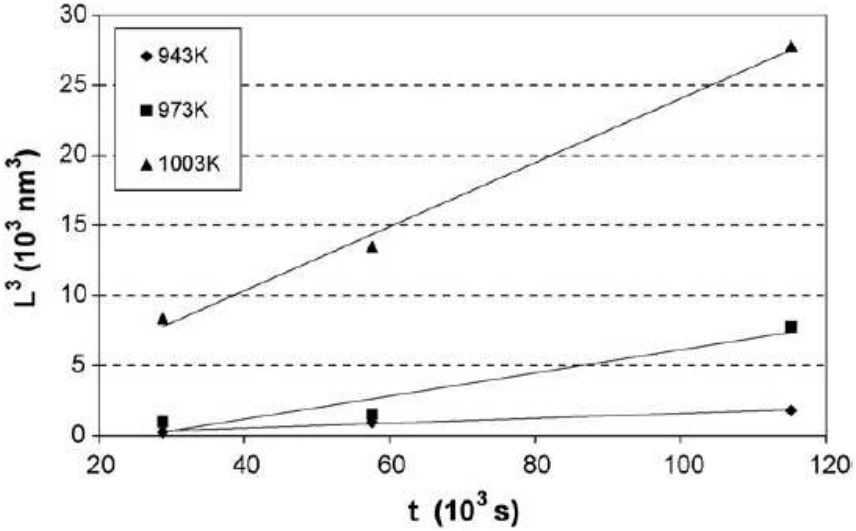
L.S.W Theory modified by Boyd & Nicholson for disc-shaped θ'' particles in Al-Cu alloys
(Acta Met., vol. 19, (1971), p. 1379



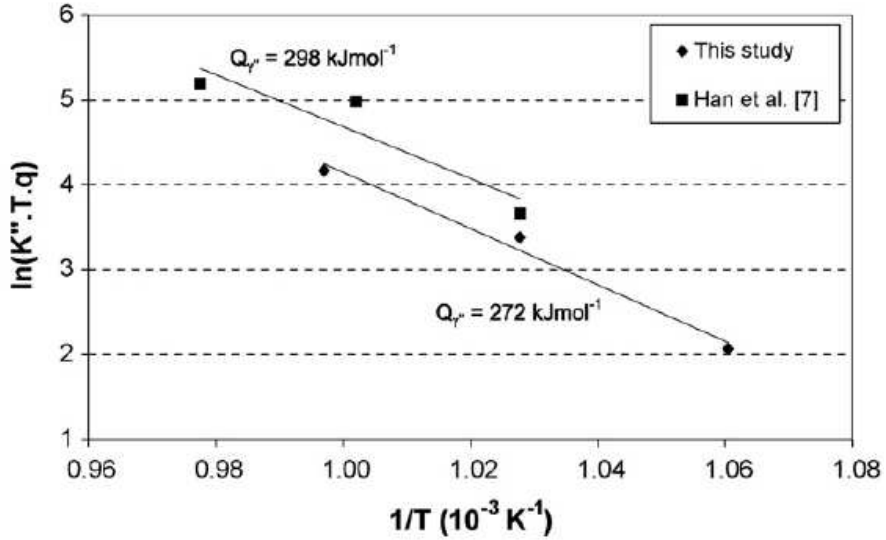
$$L^3 - L_0^3 = \frac{128}{9q\pi}\frac{\Gamma C_e V_m^2 D}{RT} t = K''t \qquad (1)$$

$$\text{with} \quad K'' = \frac{128}{9q\pi}\frac{\Gamma C_e V_m^2 D_0}{RT}\exp\left(-\frac{Q_{\gamma''}}{RT}\right) \qquad (2)$$

q = e/L ; Γ : interfacial energy ; C_e : Constant



Inconel 718 – Evolution of the diameter of disc-shaped γ'' precipitates with time

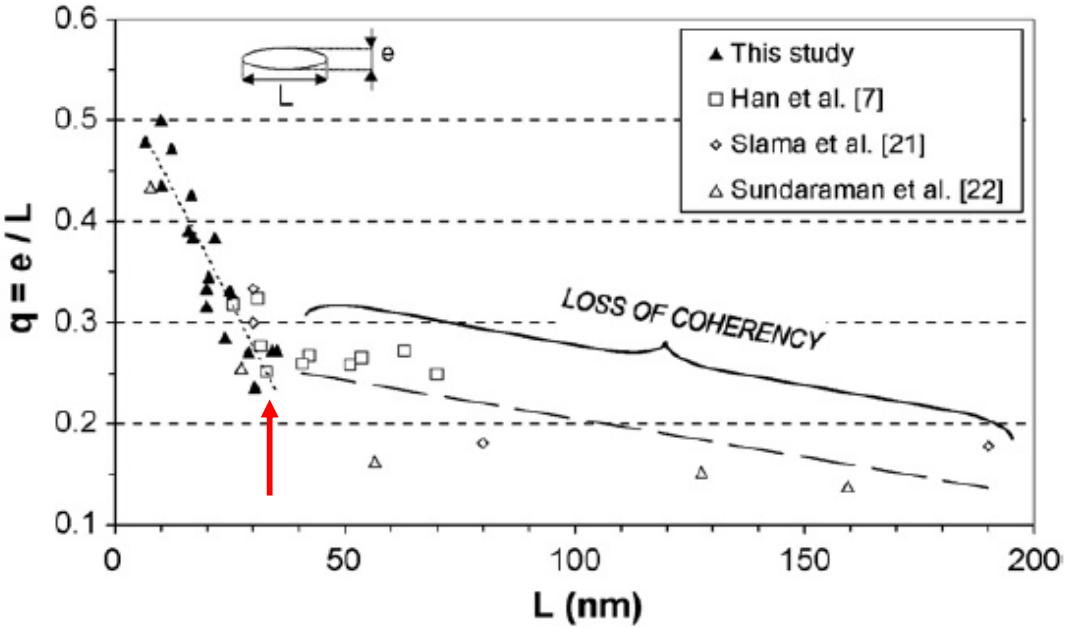


Determination of activation energy [7] : *Han et al., Mat. Sci., vol. 16, 1982, p. 555*

ASPECT RATIO q = e/L

A. Devaux et al., Mat. Sci. Eng., vol.A 486, (2008), pp. 117-122

Minimize the total (elastic + surface) energy → Determination of Γ
Elastic(isotropic) energy calculated from Eshelby theory *(Prog. Solid. Mech., vol. 2, 1961, p. 87)*
See also : *R. Cozar, A. Pineau, Scripta Met., vol. 7, 1973, p. 851*



Inconel 718 – Variation of aspect ratio with particle size

Data for calculating Γ

Coherency strains $e_{11} = 6.67 \times 10^{-3}$
$e_{33} = 2.86 \times 10^{-2}$

Shear modulus $\mu = 57.1$ GPa
Poisson's ratio $\upsilon = 0.33$

$$\Gamma = (95 \pm 17)\ \mathrm{mJ / m^2}$$

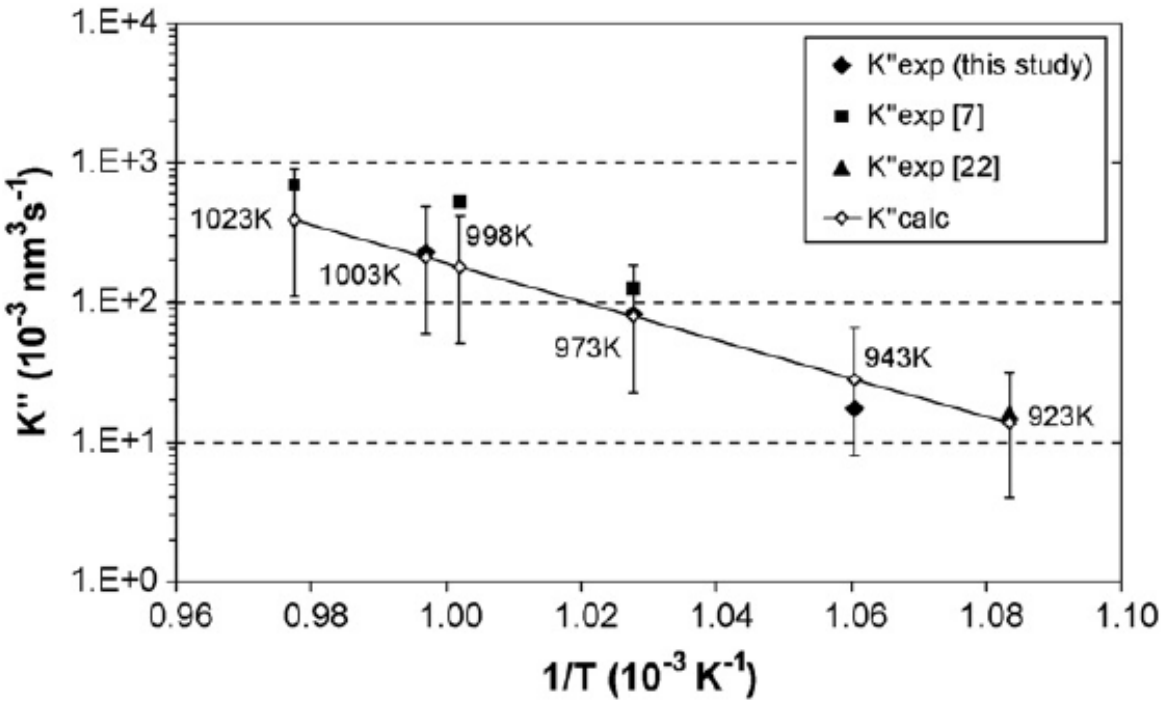
Compare with 145 mJ/m^2

in an Fe-Ni-Ta Alloy.

A. Devaux et al., Mat. Sci. Eng., vol.A 486, (2008), pp. 117-122

LSW Constant calculated at 973°K

Int. Energy	Γ	$= (95 \pm 17)$ mJ m^{-2}
Mol.Vol. of γ''	V_m	$= 2.92 \times 10^{-5}$ m^3 mol^{-1}
Aspect ratio	q	$= 0.35 \pm 0.05$
Dif. Prefactor	D_0	$= 8.8 \times 10^{-5}$ m^2 s^{-1}
Act. Energy	$Q_{\gamma''}$	= 272 KJ mol^{-1}
Dif. Coefficient	D	$= 2.2 \times 10^{-19}$ m^2 s^{-1}
Nb Concentration	C_e	= 2560 mol m^{-3}



LSW Constant (Theory & Exp.)

[7] *Han et al., Met. Sci., vol.16, 1982, p. 555*

[22] *Sundaraman et al., Met. Trans., vol.23A, 1992, p. 2015*

γ' /γ'' COPRECIPITATION IN INCONEL 706 ALLOY : A 3D FINITE ELEMENT STUDY (1)

V. Kindrachuk et al., Met. Sci. Eng., vol. A 417, 2006, pp. 82-89

ANISOTROPIC CALCULATIONS (Not for BCT Phase)

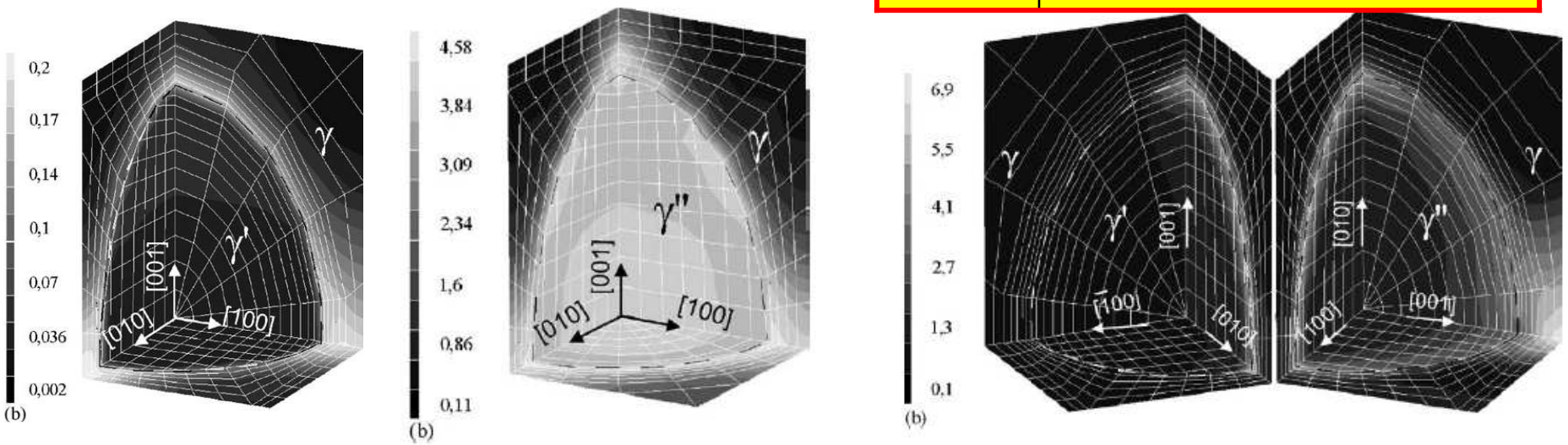
Material	C_{11} (GPa)	C_{12} (GPa)	C_{44} (GPa)	A
γ matrix	170	110	90	3
γ'	200	140	100	3.3
γ''	200	140	100	3.3

$$A = 2\,C_{44} / (C_{11} - C_{12})$$

Phase	Total Strain Energy per Precipitate
γ''	1.7×10^{-17} J ie.~ 250 KJ/m^3 or ~10 J/mole
γ'	4×10^{-19} J
γ' + γ''	5.64×10^{-18} J

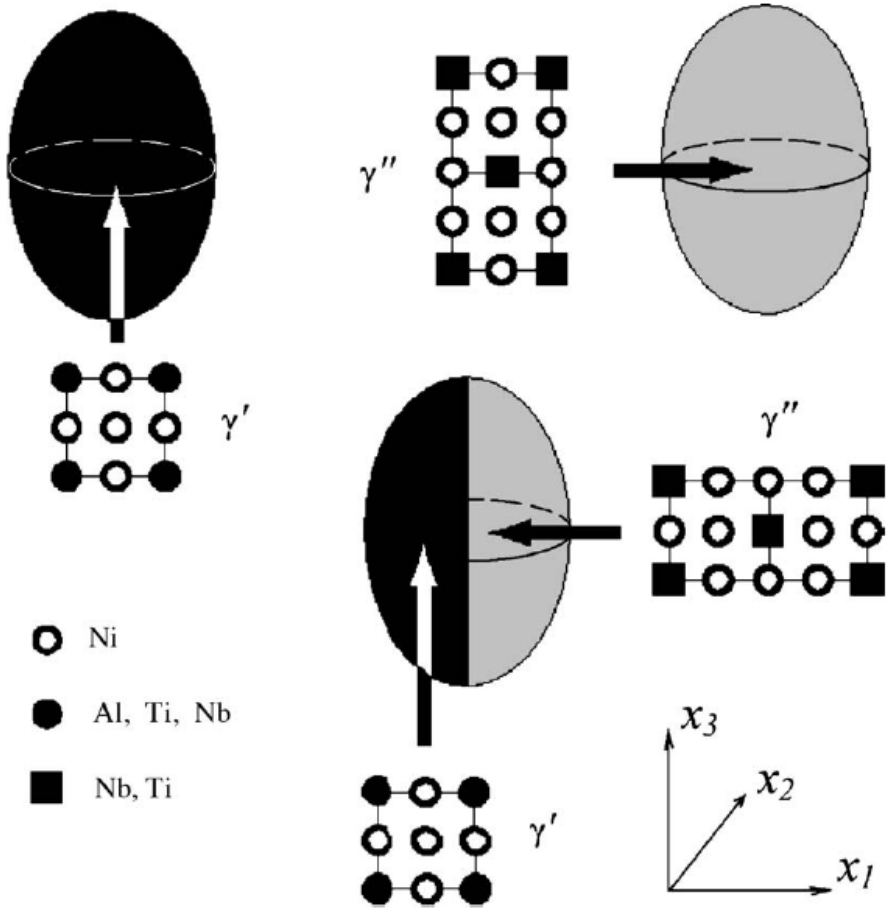
γ' $e_{11} = e_{22} = e_{33} = -0.0033$

γ'' $e_{11} = e_{22} = -0.0061$; $e_{33} = 0.053$



γ' /γ'' COPRECIPITATION IN INCONEL 706 ALLOY : A 3D FINITE ELEMENT STUDY (2)

V. Kindrachuk et al., Met. Sci. Eng., vol. A 417, 2006, pp. 82-89



Schematic representation of the morphology of the individual and co-precipitates.
Black = γ' phase; grey = γ'' phase; white = matrix – x_1//$[100]_\gamma$; x_2// $[010]_\gamma$; x_3 // $[001]_\gamma$
Ellipsoidal precipitates : major axis 2c = 10 nm; aspect ratio c/a = 1.5; Box with 75 vol.% γ-matrix

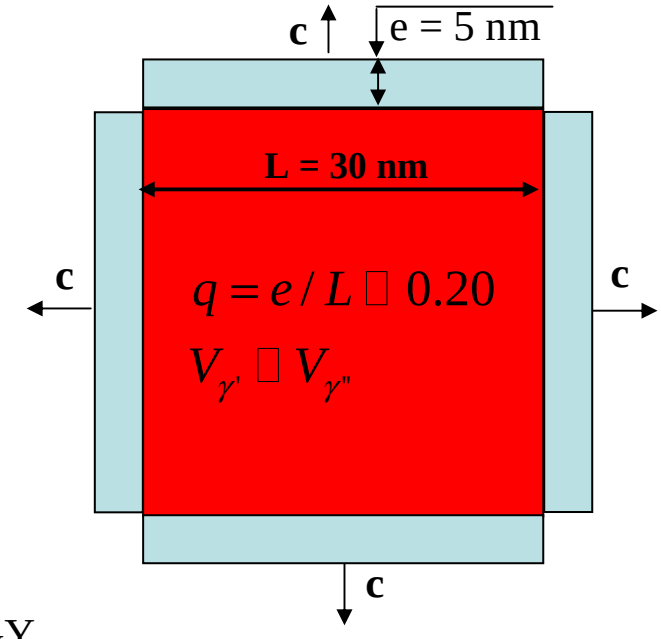
WHY γ'/γ'' CO-PRECIPITATES ARE SO STABLE ?

- DIFFUSION BARRIER

  Chemical Composition (K.J. Miller, 2001)

γ'	$Ni_3\,Ti_{0.15}\,Al_{0.36}\,Nb_{0.34}$
γ''	$Ni_3\,Ti_{0.14}\,Al_{0.02}\,Nb_{0.63}$

- SURFACE ENERGY $\Gamma_{\gamma'/\gamma''(001)}(?) \square \Gamma_{\gamma/\gamma''(001)}\left(100\,mJ/m^2\right)$



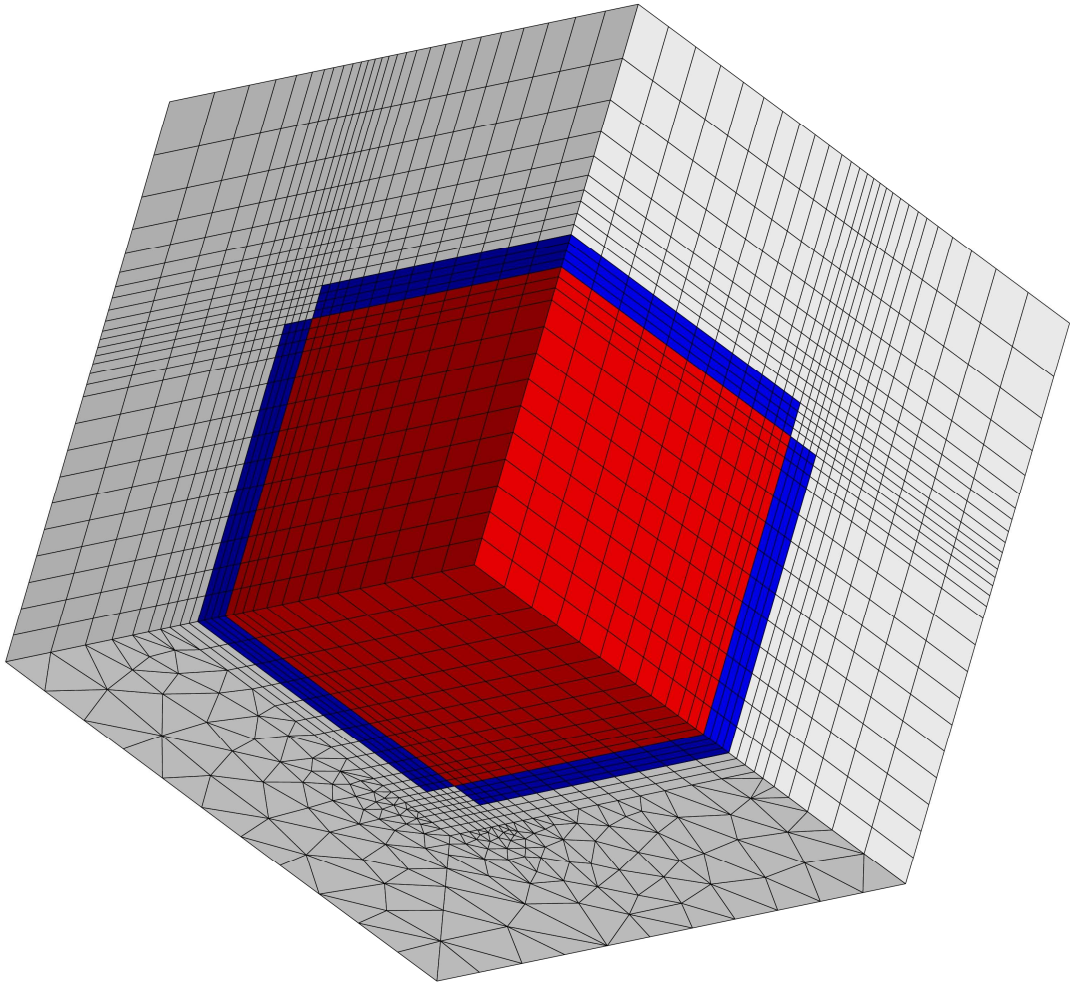
$e_{33} = 3.17 \times 10^{-2}$

(R. Cozar, A. Pineau, 1973)

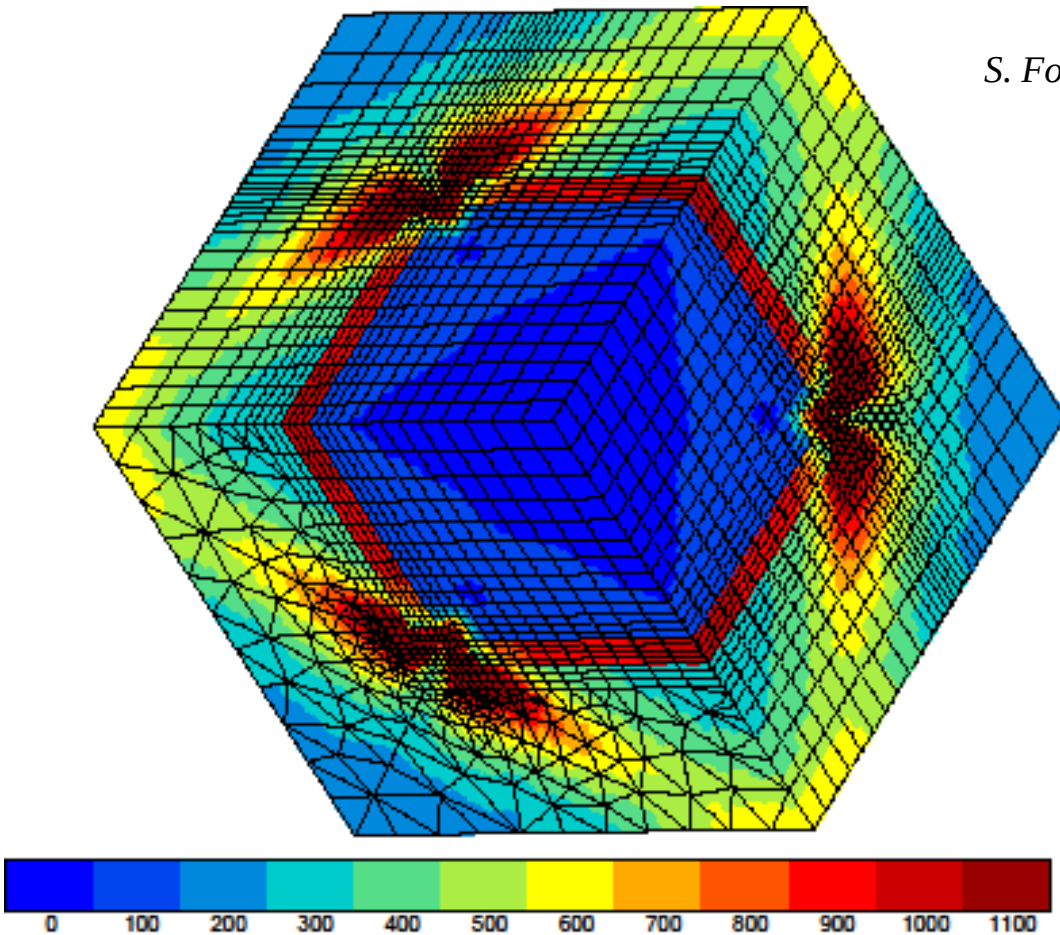
- ELASTIC STRAIN ENERGY

- Cube Shaped γ'/γ'' = Equivalent Spherical Particle with e ~ 2q $e_{33} = 1.27 \times 10^{-2}$
- 6 Disc Shaped isolated γ''; $E_{el} = 6\beta\mu/(1-2\nu)\,x\,(e_{33})^2 \quad (\beta \square 0.10 \;\; for\; q = 0.20) \quad E_{el} = 1.25\, e_{33}^2$
- « Equivalent » Sph. γ''; $E_{el} = 2\mu(1+\nu)/(1-\nu)\,x\,(e_{11})^2 = 3.71\mu(2\,q\,e_{33})^2 = 0.60\, e_{33}^2$

x 2.5



S. Forest, F; Di Rienzo, 2010



	$f_{\gamma'}$	$f_{\gamma''}$	$W_e^{\gamma'} \times f_{\gamma'}$	$W_e^{\gamma''} \times f_{\gamma''}$	ΣW_e
Non Compact γ'' Discs + γ' Cube	15%	5%	0.064	0.50	0.564
Compact Morpho	15%	5%	0.09	0.15	0.24

PRELIMINARY CONCLUSIONS

1. Rules based on electronic concentration for the formation of γ'' phase: e/a ~ 8.65
   But the composition must be known before the calculations !
2. Orthorhombic δ phase can be nucleated from sheared γ'' particles
3. Shearing of γ'' phase by perfect dislocations is difficult. This produces a strengthening effect added to the strong coherency stresses along c axis
4. Coherent disc-shaped γ'' particles change their aspect ratio during coarsening
   Interfacial energy ~ 100 mJ/m^2
5. Coarsening of coherent γ'' particles occurs relatively slowly. Controlled by Nb diffusion ?
6. Compact morphology is extremely stable . Elastic energy + Diffusional barrier

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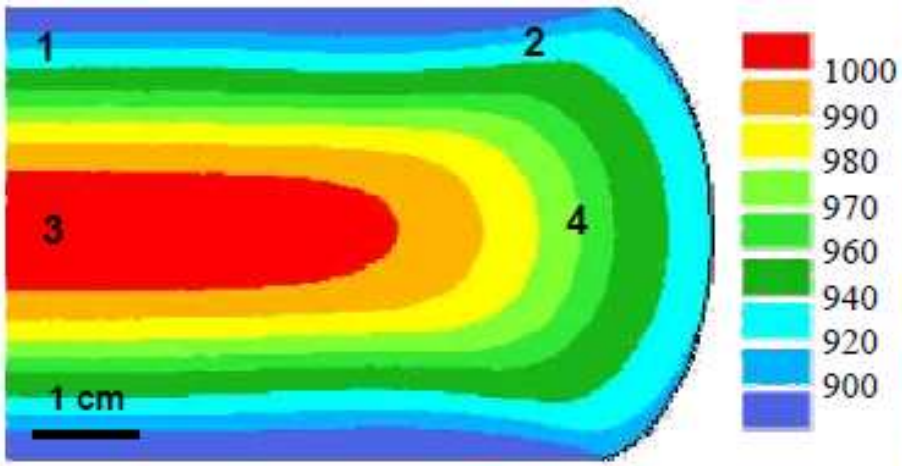
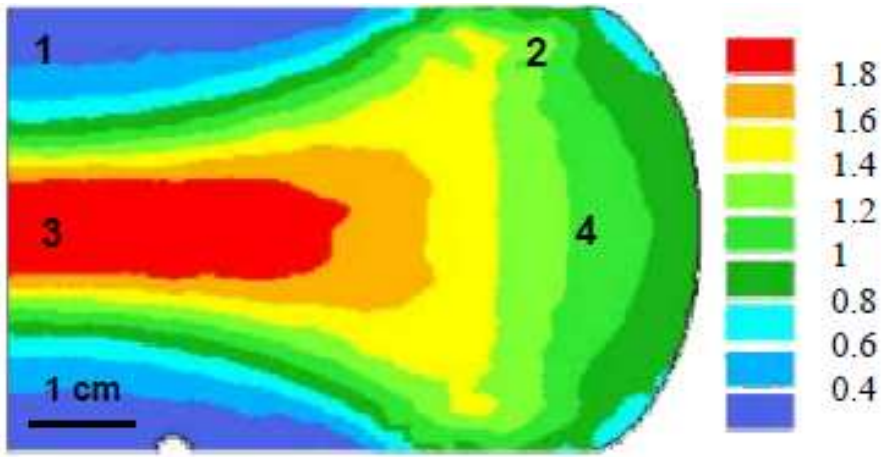
FEM SIMULATIONS OF HOT FORGING

DIRECT AGED MATERIAL (DA 718)



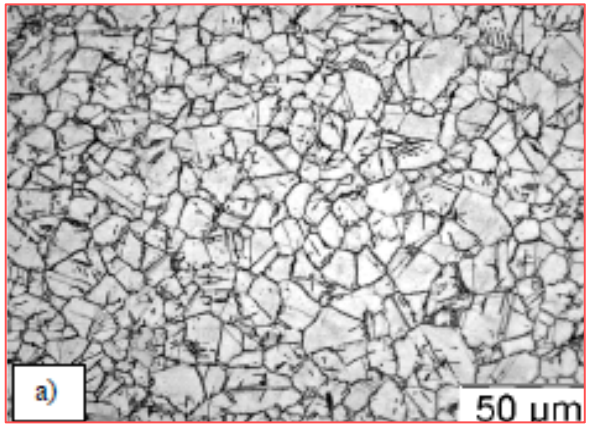
Temperature Distribution at the End of the 2nd Forging Operation

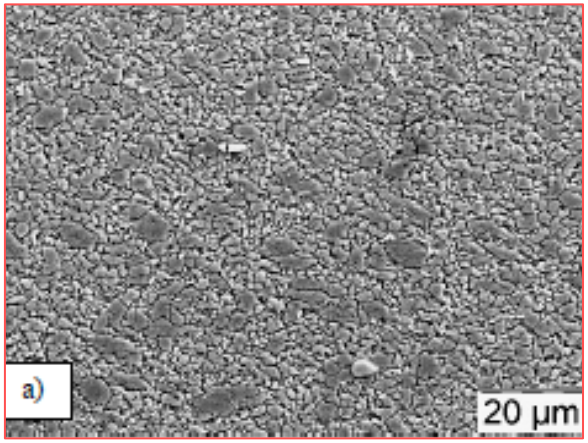


Cumulative Strain Distribution (1st + 2nd Steps)

GRAIN SIZE & δ PHASE DISTRIBUTION (1)

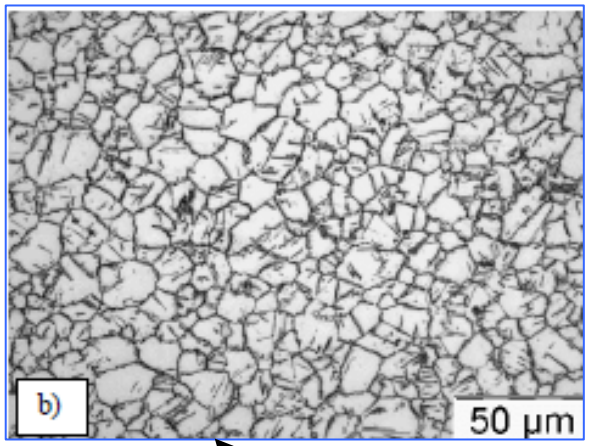
DA
d = 13 µm

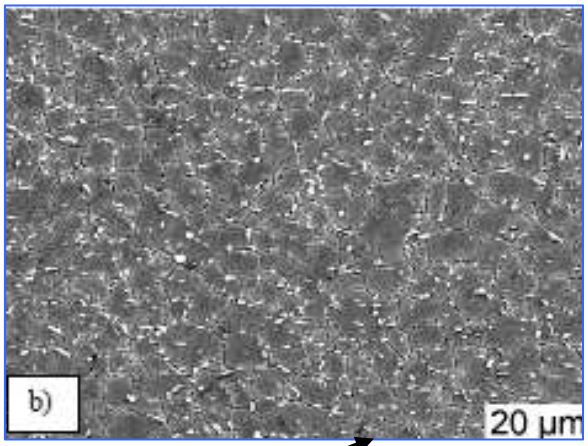




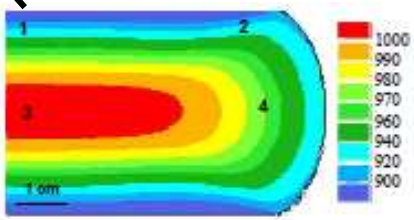
DA
d = 3 µm

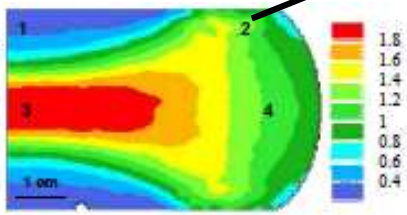
ST
d = 13 µm





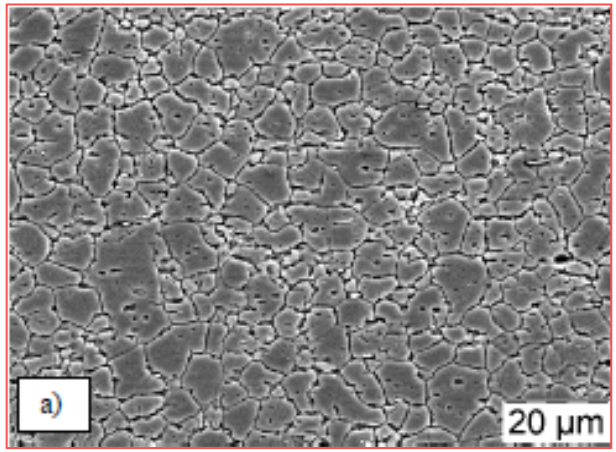
ST
d = 7 µm

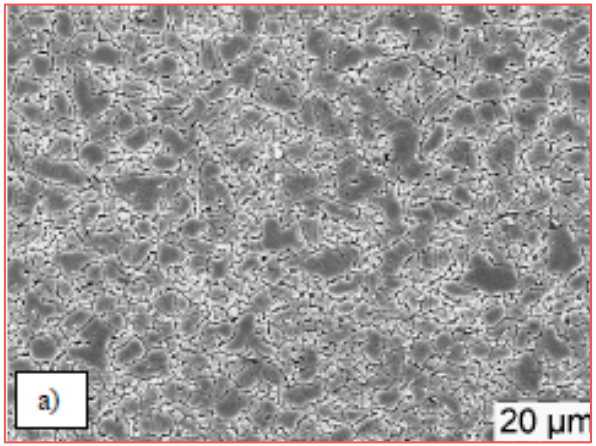




GRAIN SIZE & δ PHASE DISTRIBUTION (2)

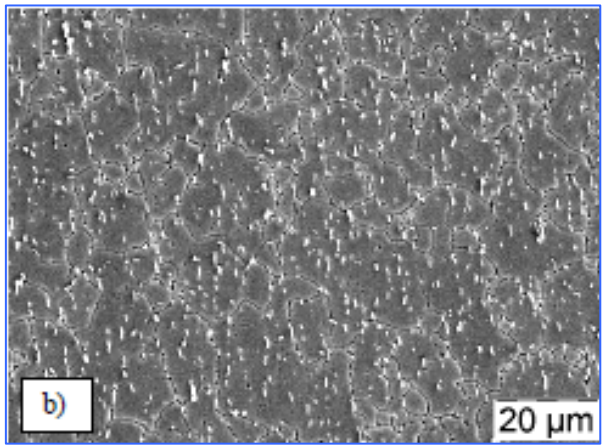
DA
d = 6.5 µm

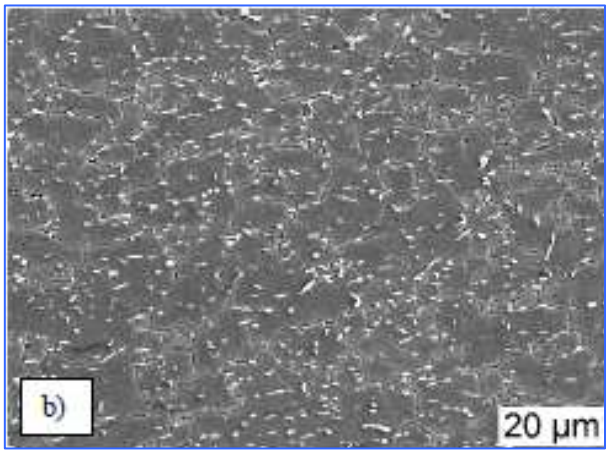




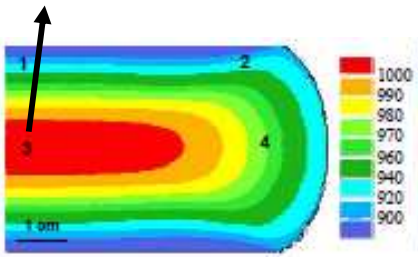
DA
d = 5.5 µm

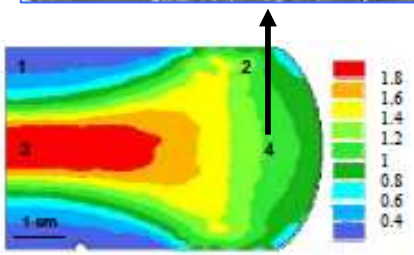
ST
d = 12 µm

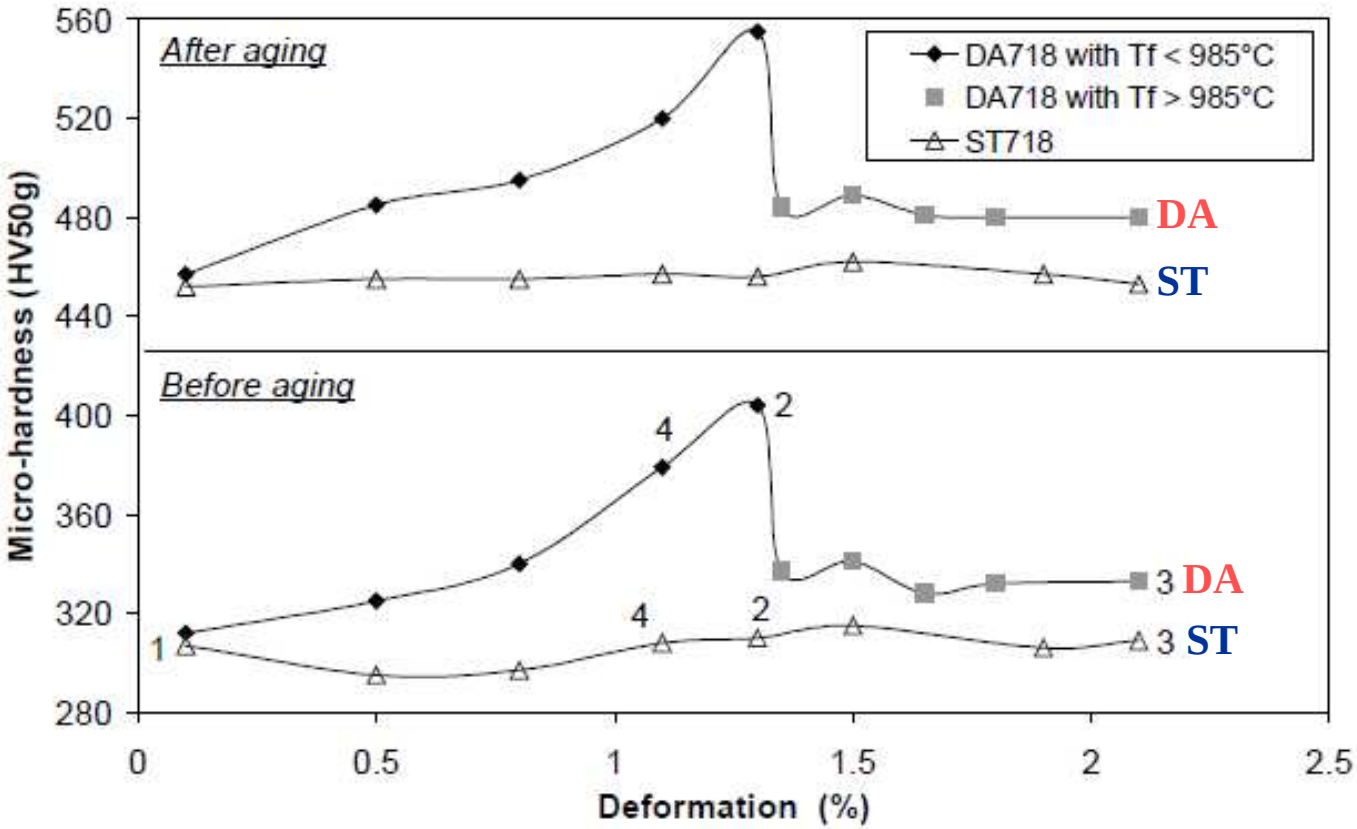




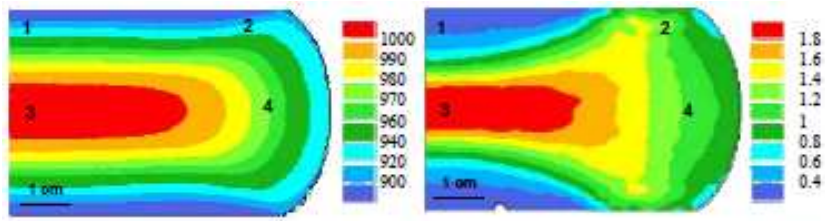
ST
d = 10 µm



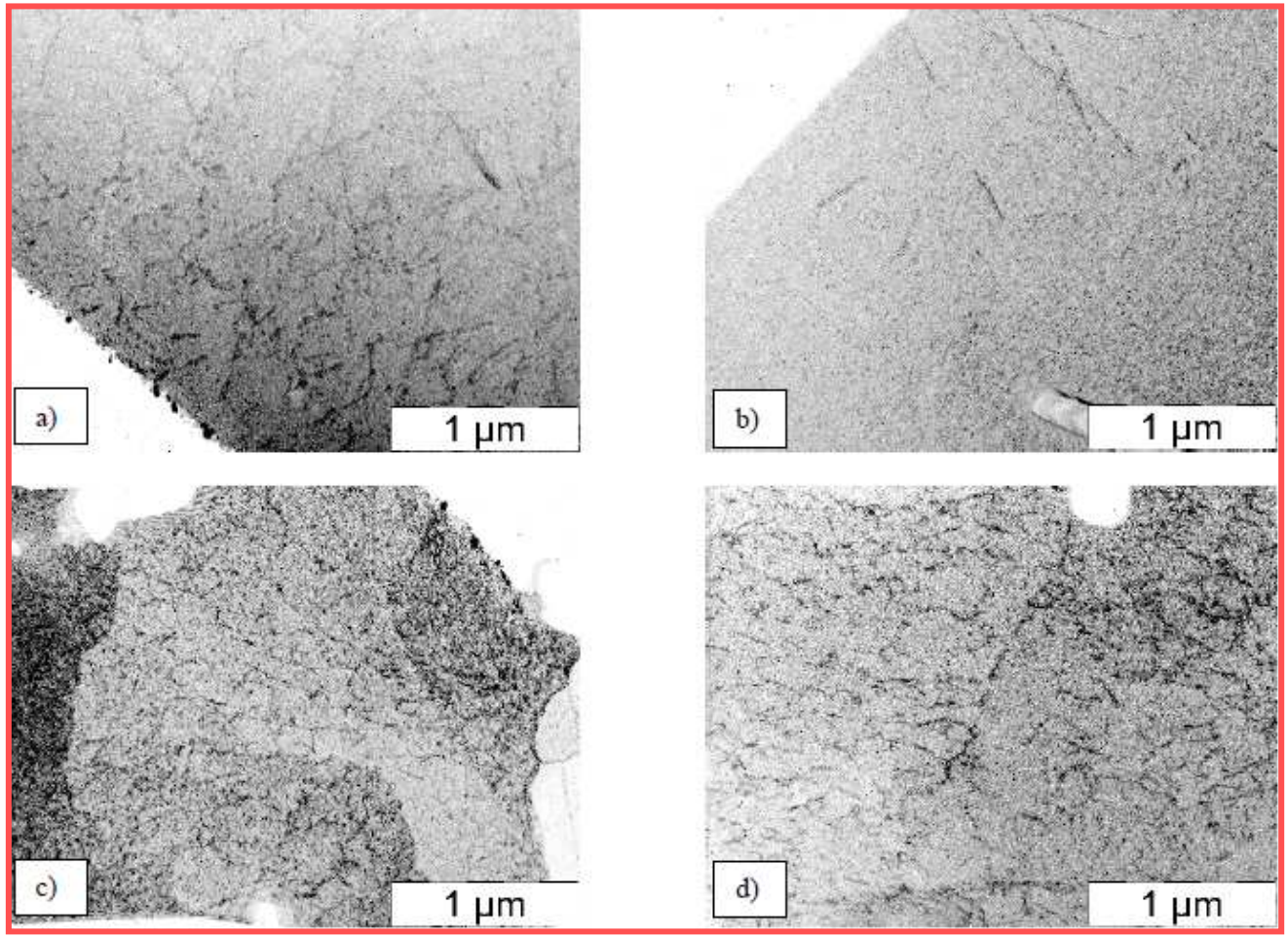




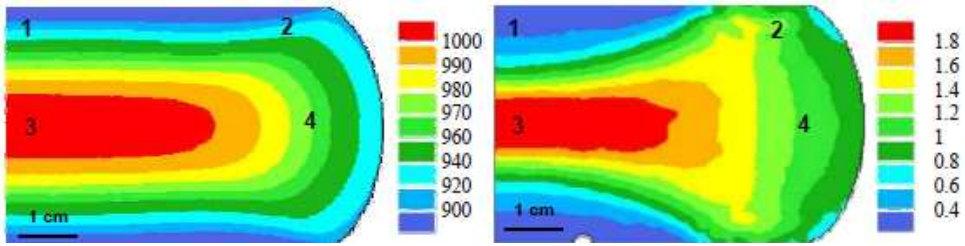
Hardness of ST 718 and DA 718 before and after aging



Temperature (°C) field at the end of the second forging Eco-deformation field cumulated (first + second steps)

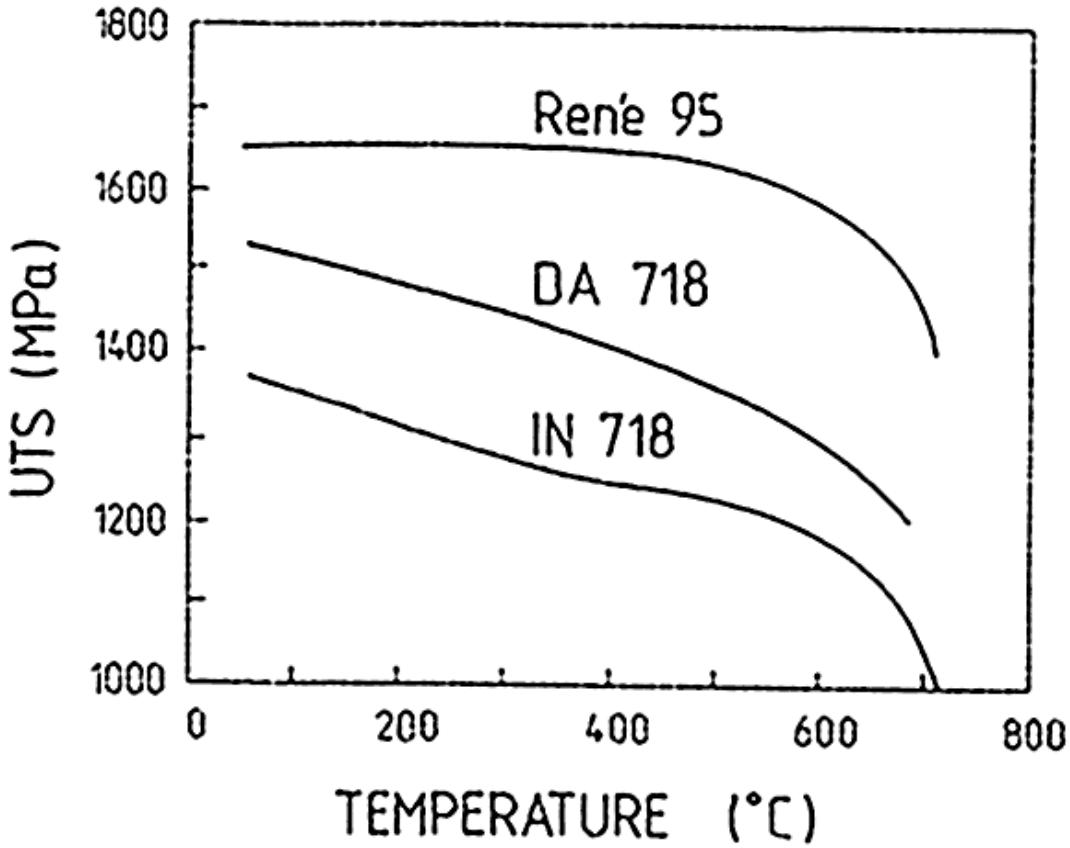


Dislocation densities (TEM) a) Zone 1; b) Zone 3; c) & d) Zone 4



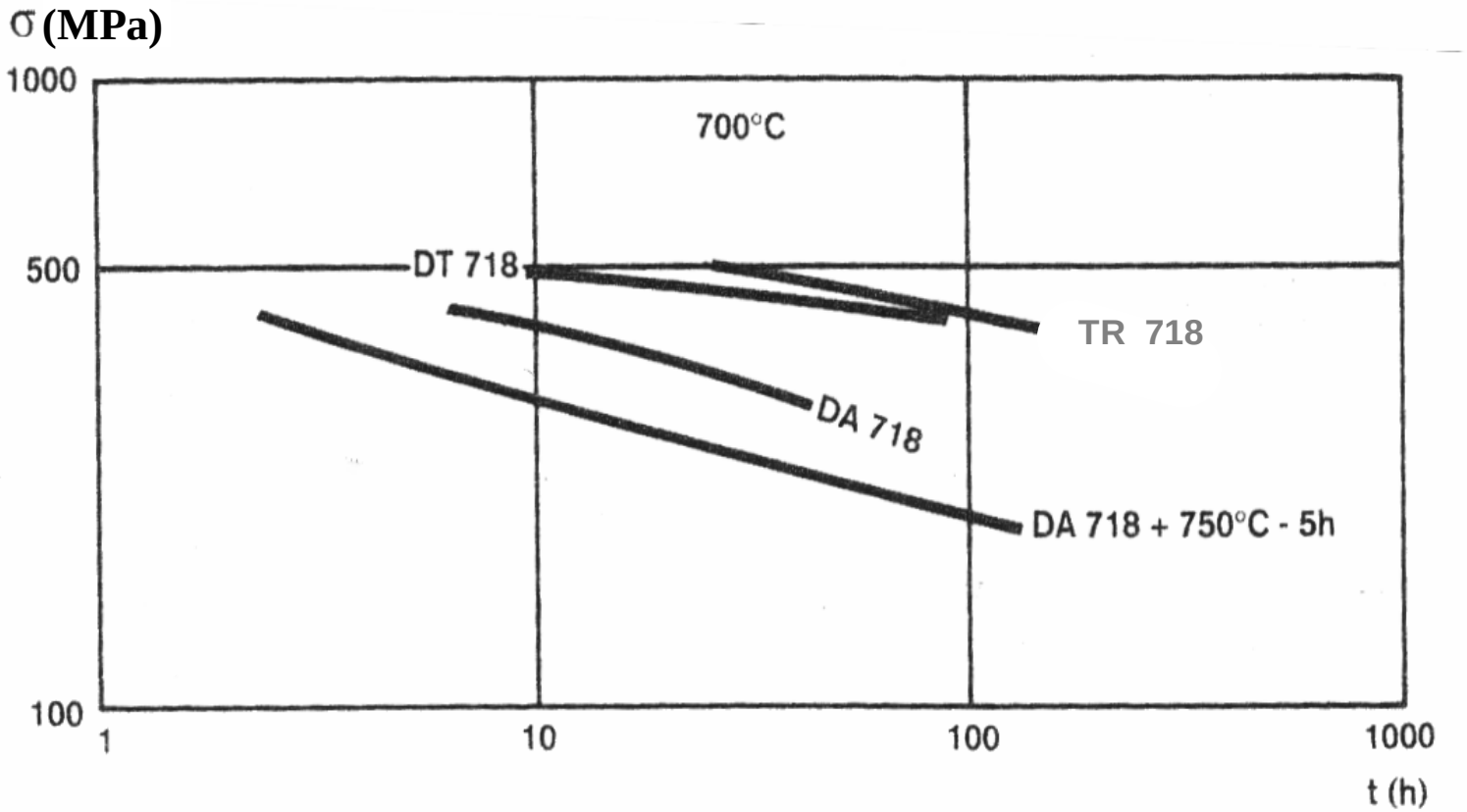
ALLOY 718 & René 95

TR : AS QUENCHED + AGED **DA : DIRECT AGING**

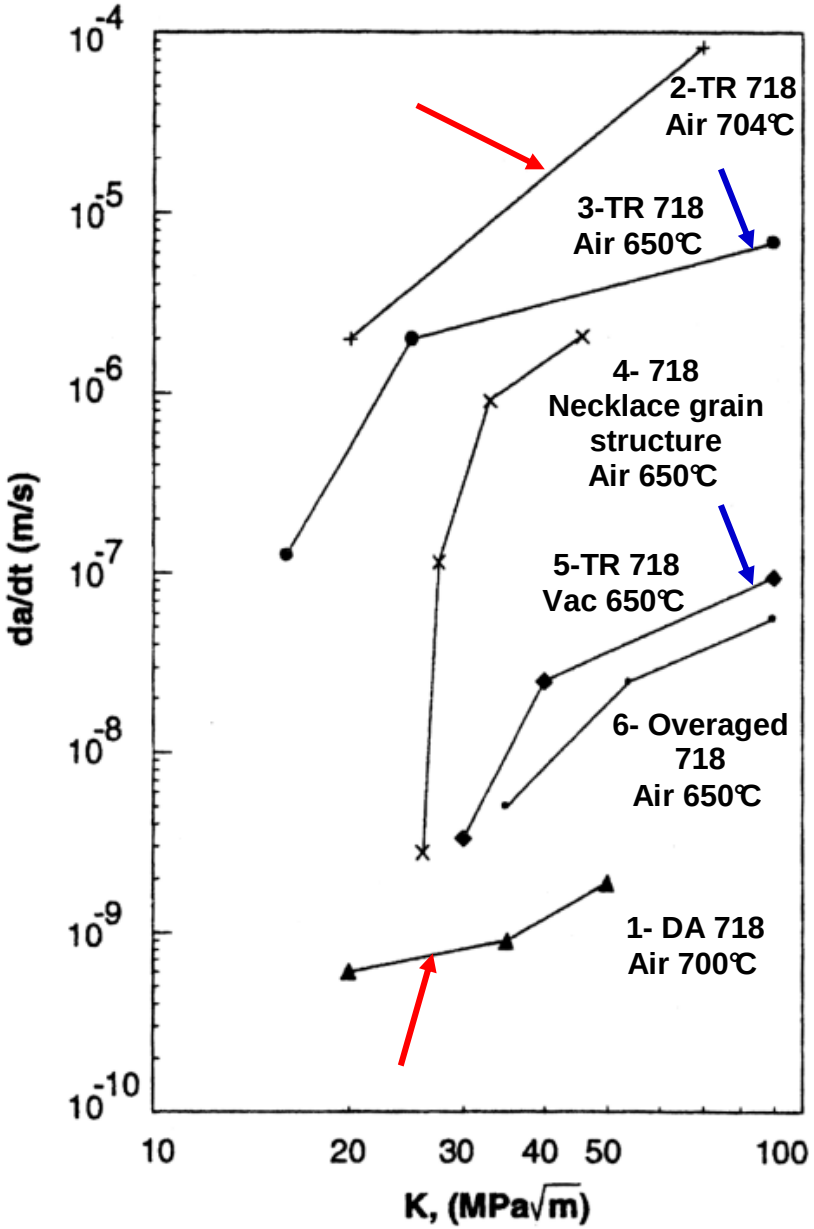


ALLOY 718

Curves for 0,2% Creep Strain at 700°C



TR : AS QUENCHED + AGED **DA : DIRECT AGING**

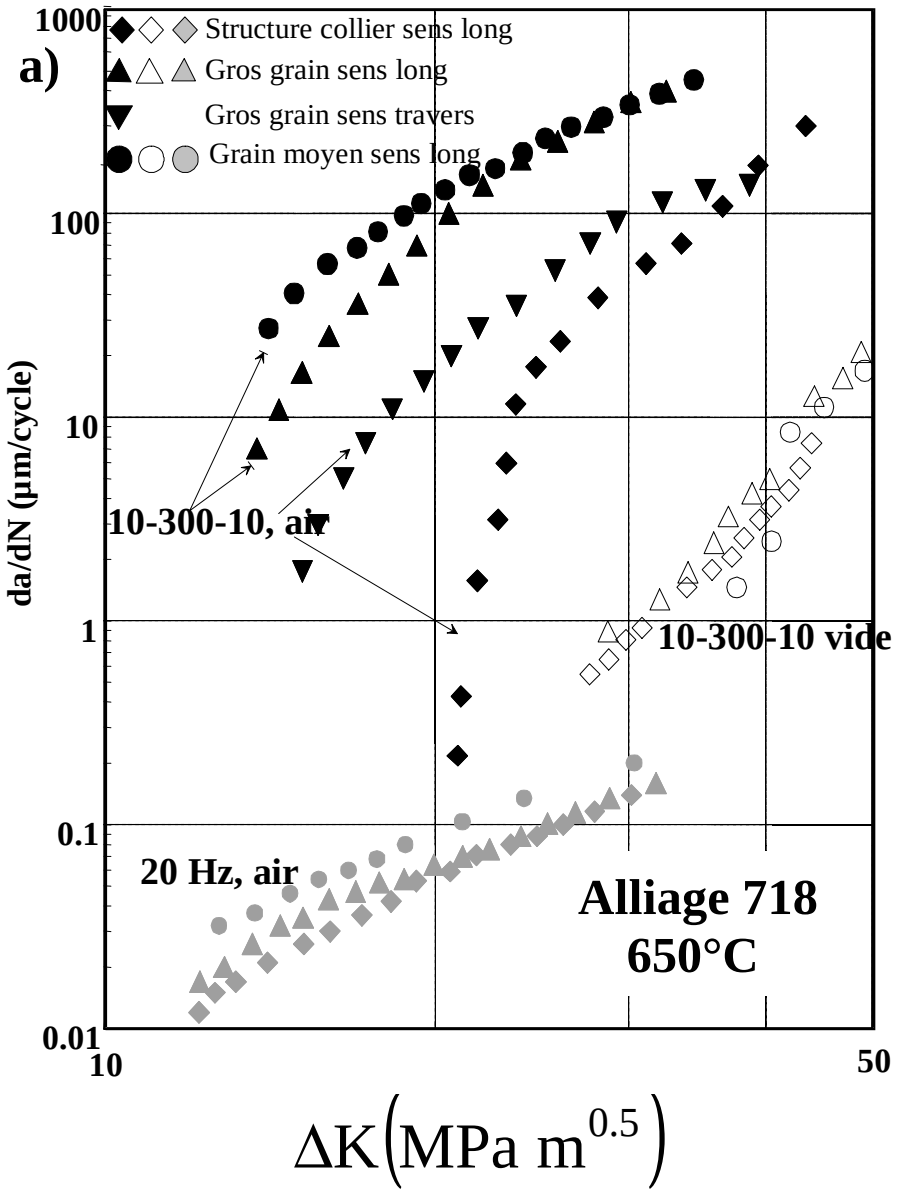


CREEP CRACK GROWTH RATE IN ALLOY 718

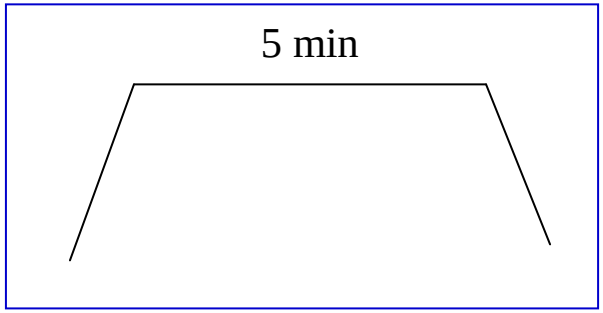
INFLUENCE OF MICROSTRUCTURE AND ENVIRONMENT

TR : AS QUENCHED (~950°C) + AGED (720°C - 8h + 620°C - 8h)

DA : DIRECT AGING (720°C - 8h + 620°C - 8h) after FORGING



FATIGUE CRACK GROWTH AT ELEVATED TEMPERATURE



INFLUENCE OF GRAIN SIZE (and SHAPE) and ENVIRONMENT

ALLOY 718 and OTHER DERIVATIVES BASED ON γ'' PRECIPITATION

A. Pineau
Centre des Matériaux – Mines ParisTech
UMR CNRS 7633
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I. INTRODUCTION : Alloys Strengthened by γ'' Precipitates

II. PHYSICAL PROPERTIES OF γ'' PHASE and γ'/γ '' COPRECIPITATES
- II.1. Atomic Structure
- II.2. Composition
- II.3. Dislocations in γ'' phase
- II.4. Compact Morphology
- II.5. γ'' Shape and Coalescence

III. MECHANICAL PROPERTIES OF INCONEL 718 (Introduction)

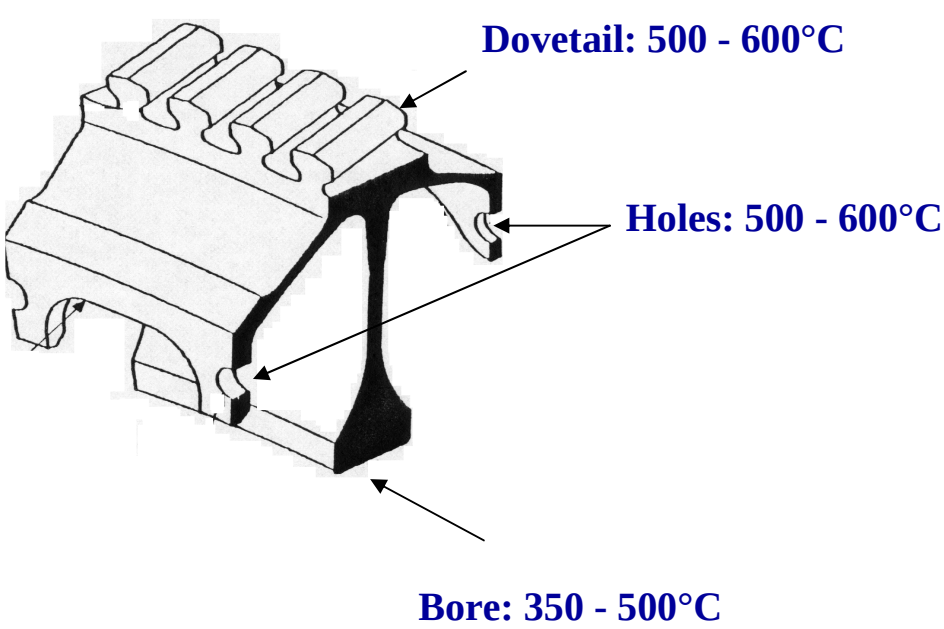
IV. HIGH TEMPERATURE FATIGUE OF INCONEL 718 in RELATION WITH MICROSTRUCTURE
- **Crack Initiation : Grain Size and Initiation from Carbide Particles**

V. CONCLUSIONS & PROSPECTS

FATIGUE : CRACK INITIATION FROM CARBIDES & NITRIDES

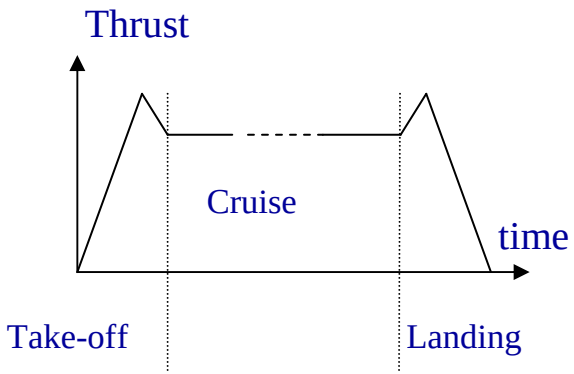
- **Industrial context**
- **LCF tests on Smooth Specimens**
  - Micro-Crack Initiation
  - Micro-Crack Propagation
  - Probabilistic Aspects
- **Validation using notched specimens**
  - Experimental results
  - Finite Element Calculations
  - Comparison between experiments and life prediction calculations
- **Conclusions and Prospects**

INDUSTRIAL CONTEXT : CIVIL AIRCRAFT TURBINE DISKS



Stress concentration zones

In718 Turbine disks

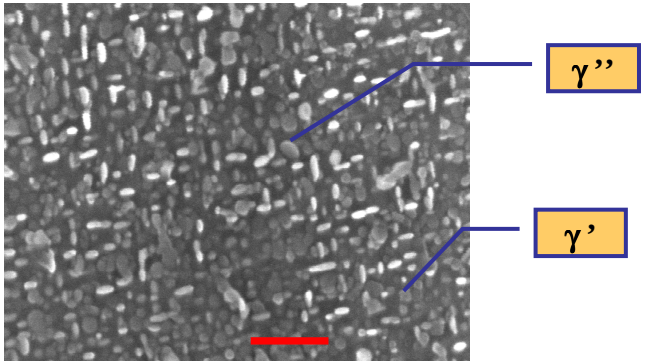


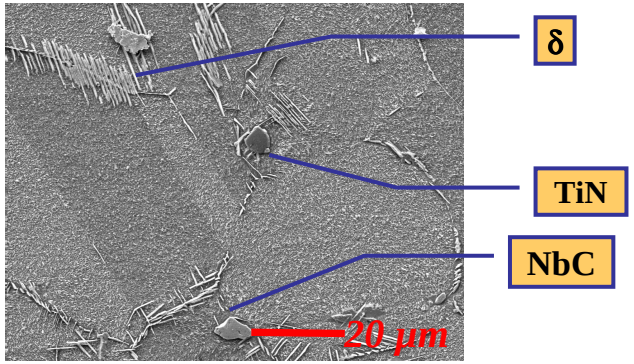
Civil flight

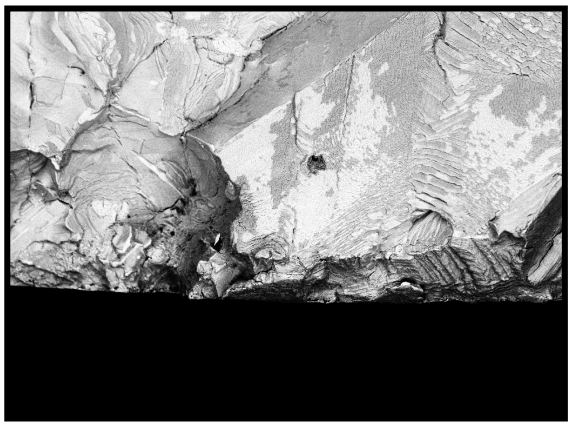
Forging route ⇒ effect on microstructure and mechanical properties

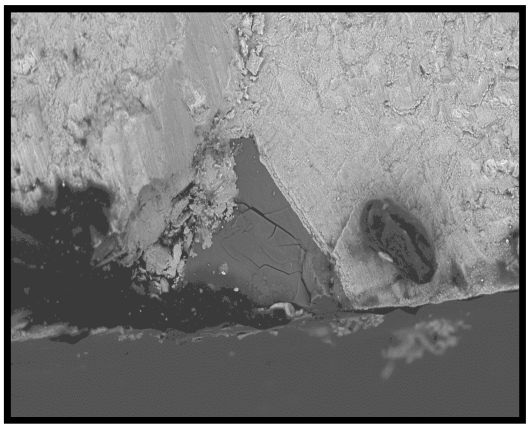
DA 718: COMPOSITION, MICROSTRUCTURE & CRACK INITIATION SITES

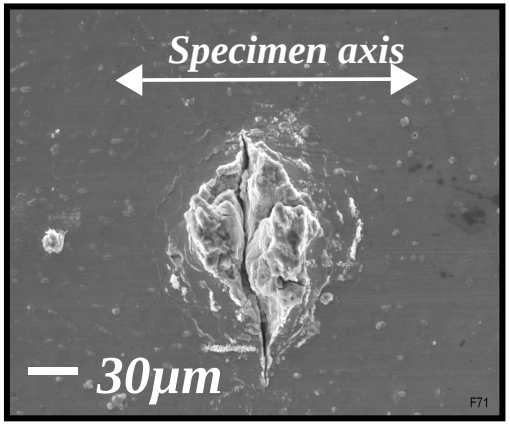
Element %	Ni	C	Cr	Fe	Nb	Mo	Ti	Al
Min	Base	0.02	17.00	15.00	**4.75**	2.80	0.75	0.30
Max	Base	0.08	21.00	21.00	**5.50**	3.30	1.15	0.70



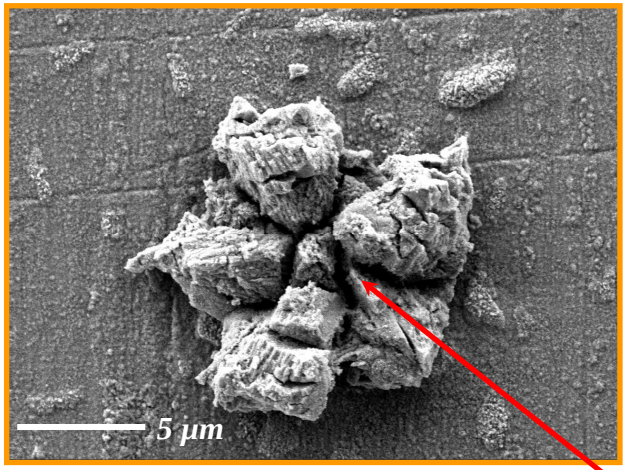


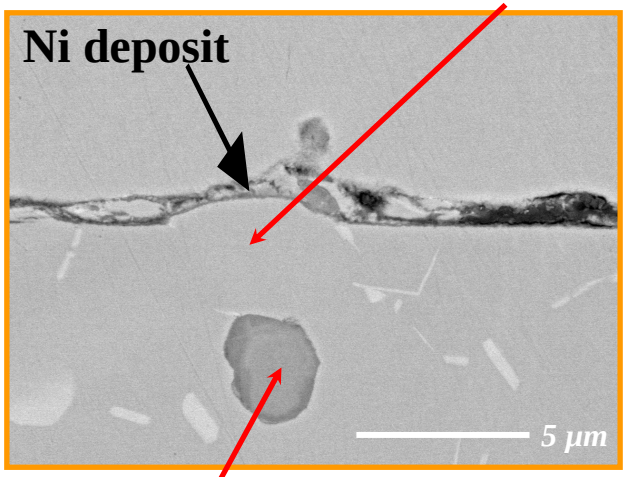


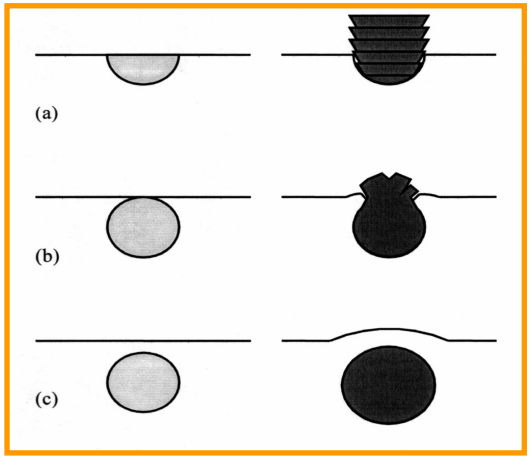




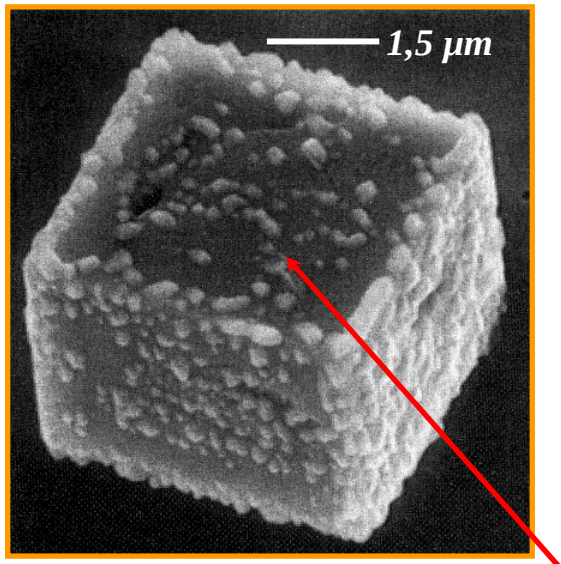
Bulge

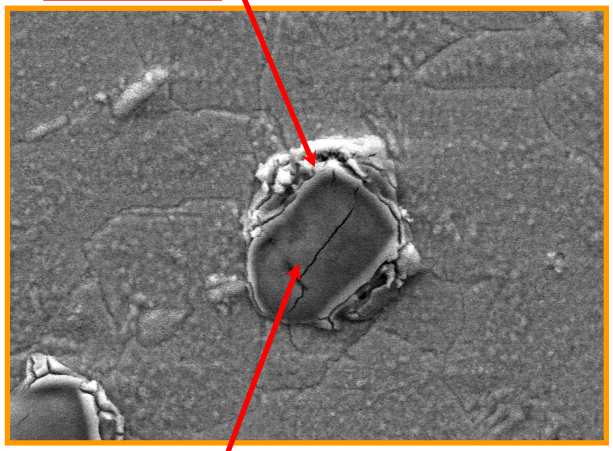


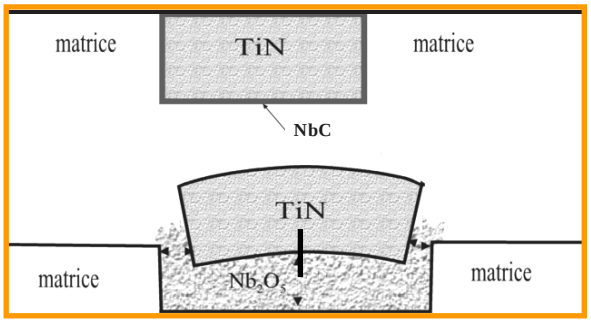




Nb_2O_5





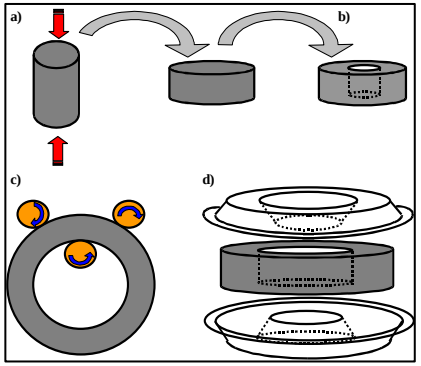


TiN

See also T; Connelley, P.A.S.Reed, J.M.Starink

Mater. Sci. Eng., vol 340 A, pp.139-154

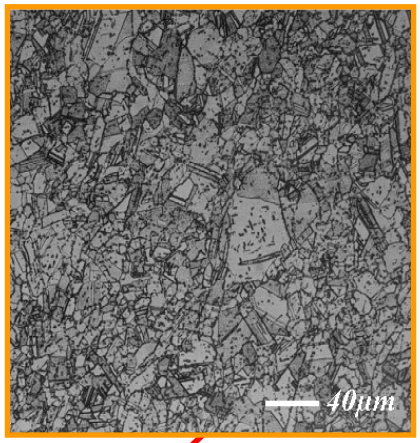
MICROSTRUCTURES AND MECHANICAL PROPERTIES IN DA 718 AFTER FORGING

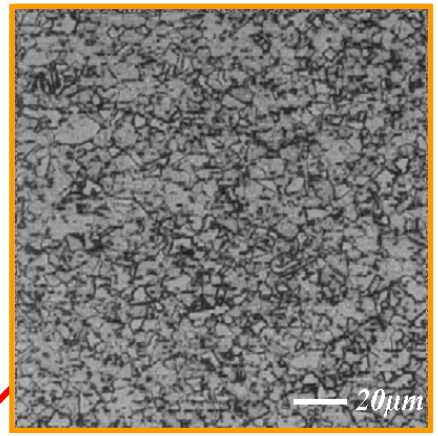


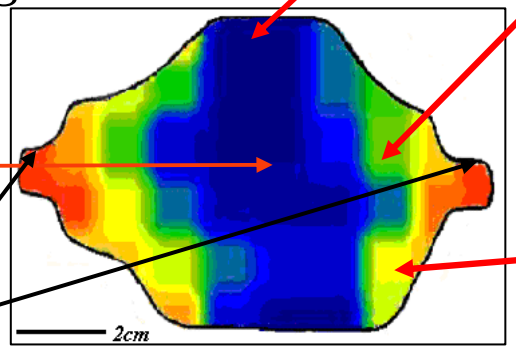
TR718 : Solutionizing : 955°C-1h;

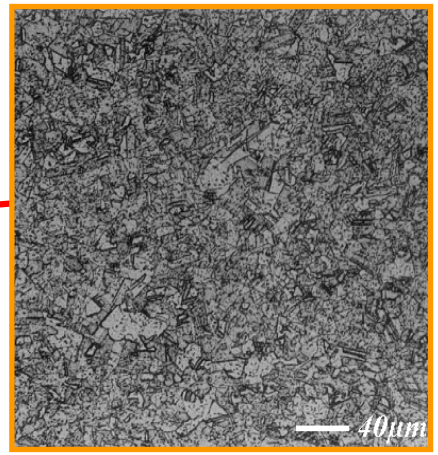
Ageing : 720°C/8h & 620°C/8h

DA718 : No solutionizing









Rotation axis

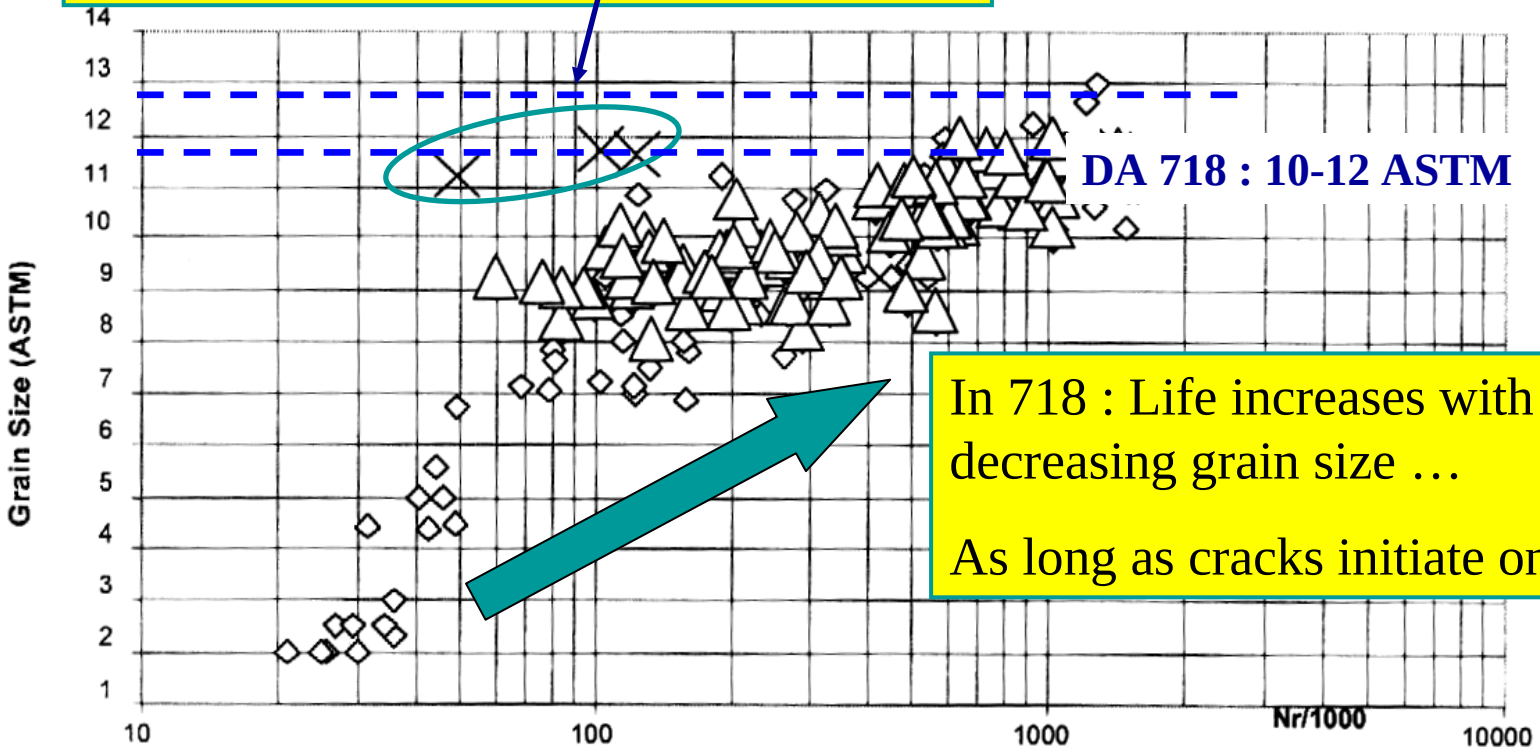
Central zone (600°C) :
Yield S = 1140 MPa
UTS ~ 1300 MPa

Peripheral zones (600°C) :
Yield S = 1240 MPa
UTS ~ 1400 MPa

HETEROGENEOUS MATERIALS

IN 718 / DA 718: MICROSTRUCTURE & CRACK INITIATION SITES

Crack initiation on carbides
= f (loading, microstructure, temperature)



In 718 : Life increases with decreasing grain size …

As long as cracks initiate on grains

Figure 2 : Variation of experimental fatigue life rupture time with the microstructure. LCF tests achieved at 350°C on INCO 718, at low frequency (1Hz) and under R=0 load ratio for strain controlled loading (between 0.52 and 0.60%)

◇ : Experimental data : crack initiation site not identified

Δ : Crack initiation located on grain

× : Crack initiation located on carbide

INDUSTRIAL DESIGN OBJECTIVES

Actual lifing methods for DA 718 turbine disks:

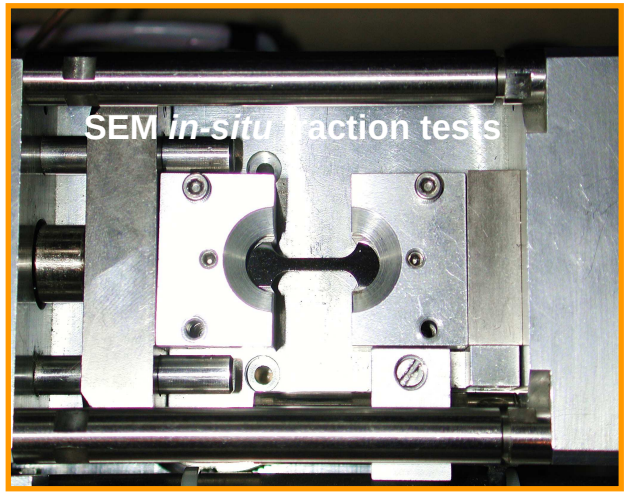
- **Based on material Wöhler- type LCF curves (numerous LCF data)**
- **Do not distinguish between crack initiation sites ⇒ high dispersion**
- **Show high conservatism for stress concentration zones**
- **Do not allow easy material and process specification / optimization**

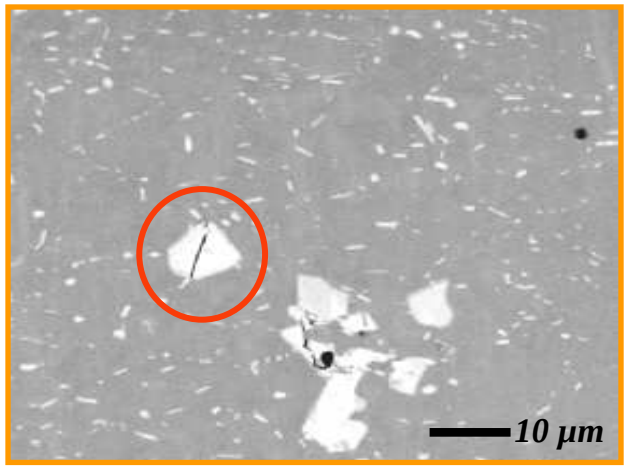
⇒ Need to take into account microscopic mechanisms involved in DA 718 fatigue properties

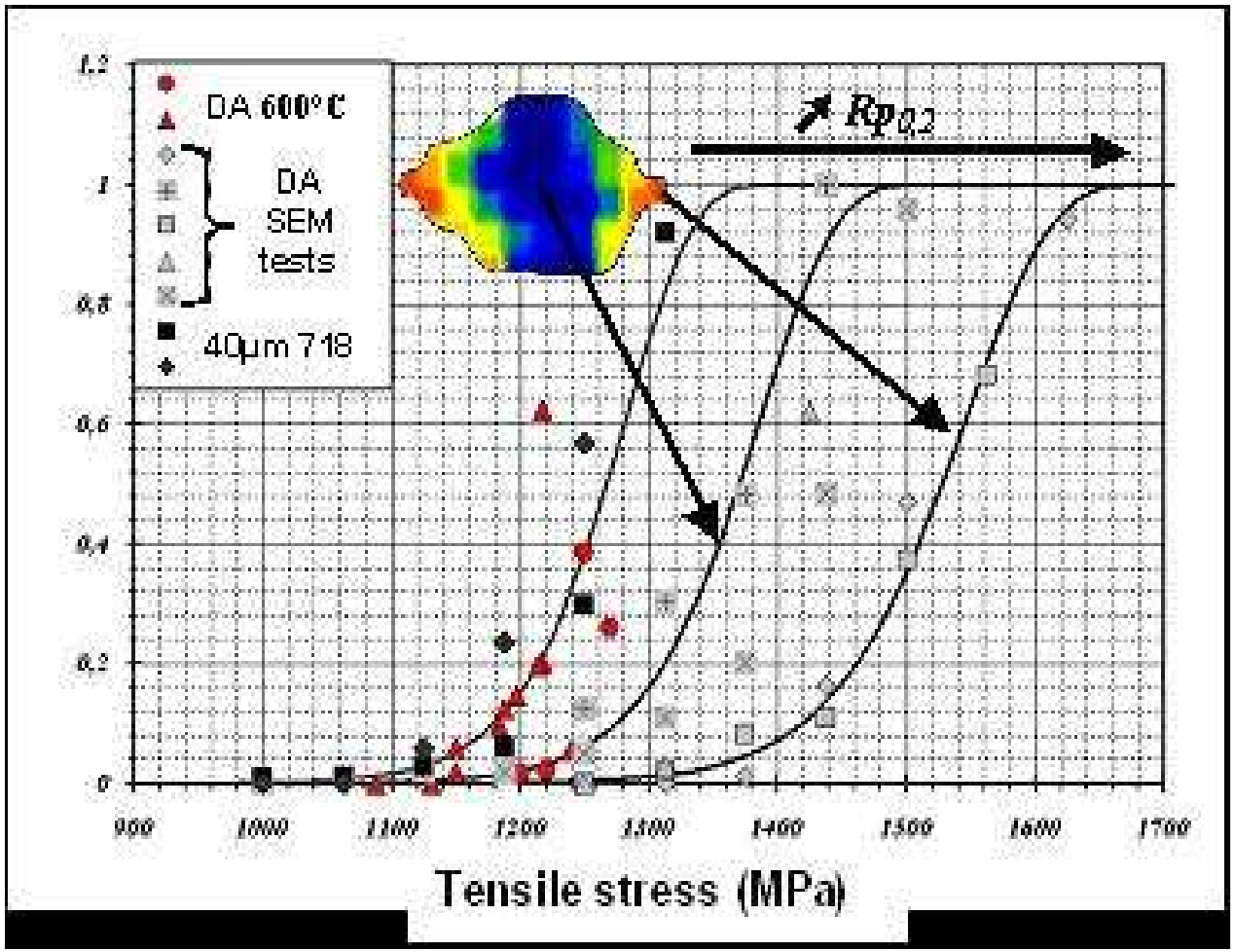
Objectives in the program:

- **Establish criteria and models to distinguish between initiation sites**
- **Better describe stress gradients effects in stress concentration zones**
- **Reduce conservatism by understanding and modeling LCF scatter**
- **Develop a numerical tool compatible with design constraints**

CRACK MICRO - INITIATION ON CARBIDES AND NITRIDES



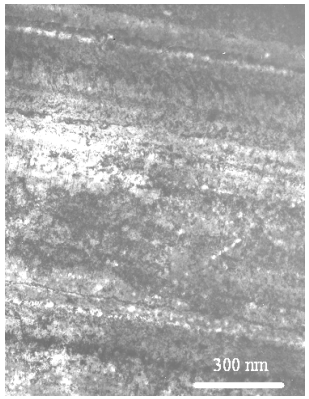




Crack initiation at 1st LCF cycle ; $P_{rupture}$ correlated to mechanical behavior

CRACK MICRO-INITIATION MODELS

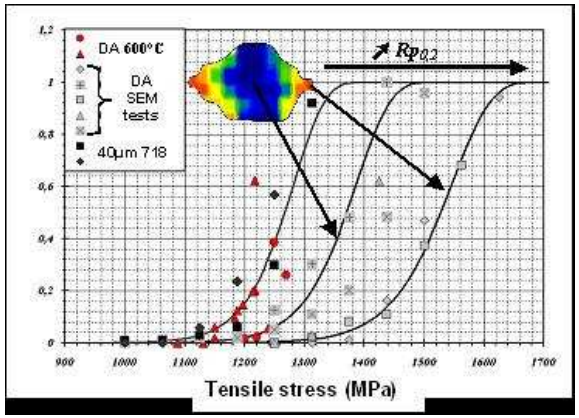
Stage I initiation



$$N_i = \frac{1}{d}\frac{A_{stageI}}{\left(\Delta\varepsilon_p\right)^2} \qquad \text{(Eq.1)}$$

- Modified Tanaka-Mura model
  - **Coherent with PSB observed in In718**
  - **Alloy average grain size considered**
  - **Initiation after N_i cycles, crack size d**
  - **Deterministic formulation**

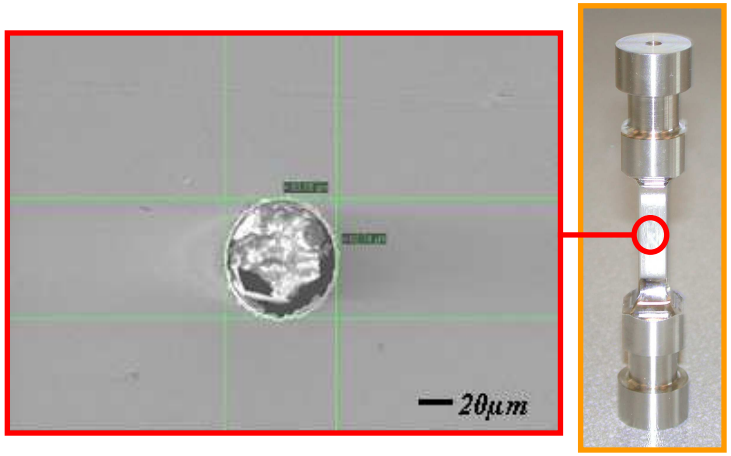
Particle initiation

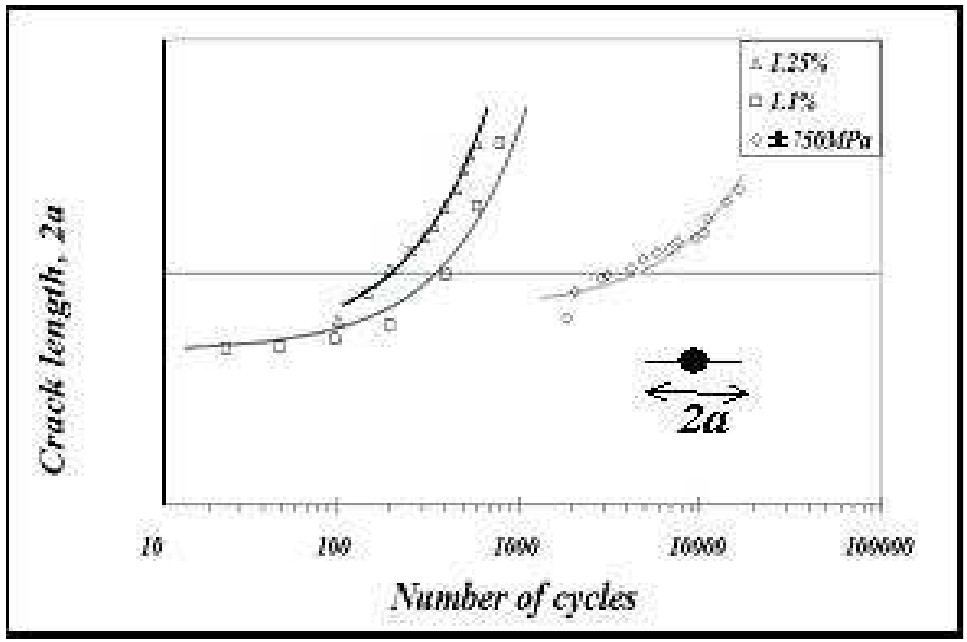


$$P_{fracture} = 1 - \exp\left(-\left[\frac{\Sigma_1 + \lambda < \left(\sigma_{eq} - Rp_{0.2}\right) >}{\sigma_u}\right]^m\right) \qquad \text{(Eq. 2)}$$

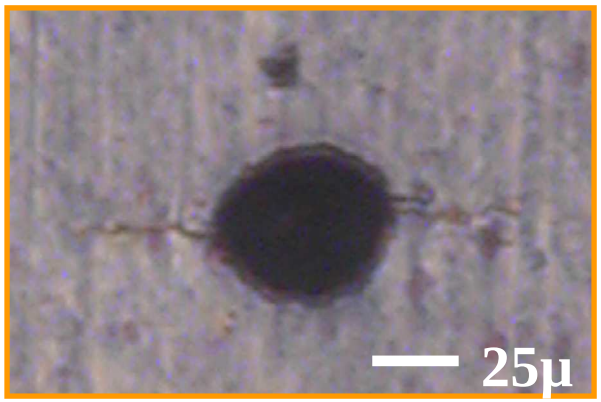
- Beremin-type formulation
  - **Initiation at 1st LCF cycle**
  - **Probabilistic model**
  - **Material behavior heterogeneities considered**

CRACK MICRO-PROPAGATION EXPERIMENTAL RESULTS & MODEL





- **Fatigue Crack growth rate testing**
- **Controlled EDM initial flow**
- **Questar (optical) crack length measurement**



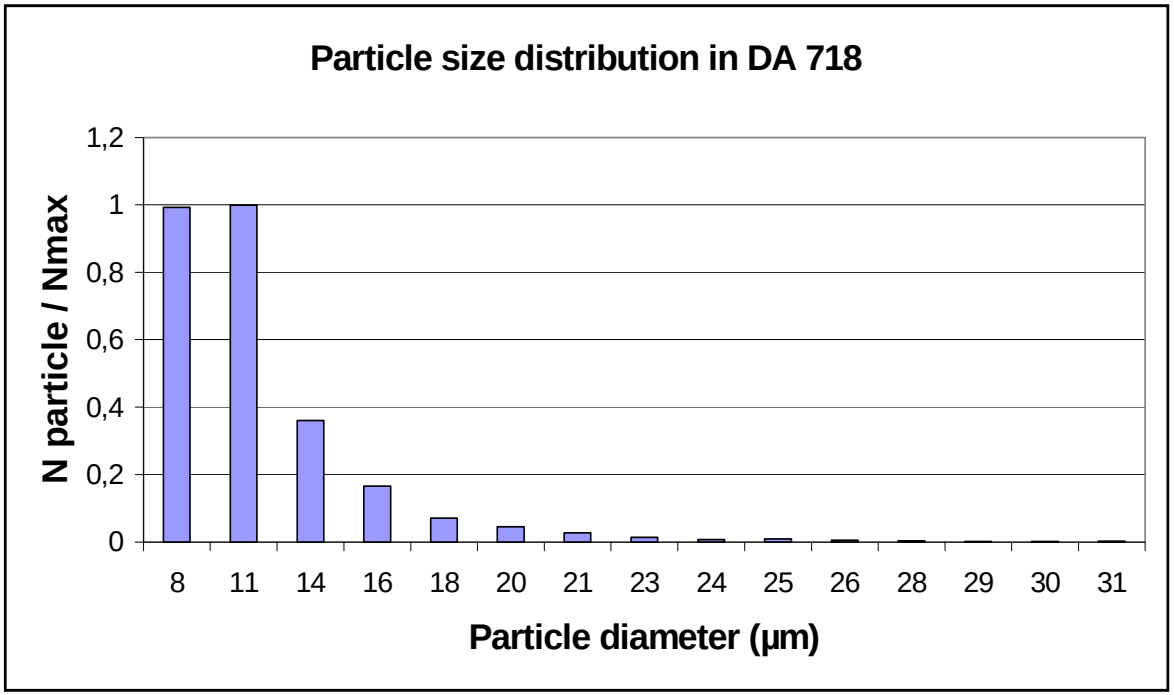
$$da/dN = \alpha.a$$

$$\alpha = \frac{\pi^2}{8}\frac{\Delta\varepsilon_p \Delta\sigma^2}{(2T)^2}\left(1+\frac{\pi^2}{8}\left(\frac{\Delta\sigma}{2T}\right)^2\right) \quad \text{(Eq.3)}$$

- **Tomkins micro-propagation model**
- **Model parameters: mech. behavior, T**
- **Direct analytical integration from a_0 to a_f**

PROBABILITY OF PARTICLE PRESENCE

- Examination on coupons taken from forged turbine disks
- Essentially carbides
- Along fibers and perpendicular to them
- Surface observed: 86 mm^2, >3000 particles
- Threshold effect on initiation observed



PROBABILISTIC MODEL

- Probability of finding particles with a diameter D_1 larger than a given diameter, D_0

$$P(D_0 \le D) = \frac{N(D_0 \le D)}{N(D_0 \le D_{\min i})} = \frac{\sum_{Dj=D0}^{D\max i} N(D_0 = D_j)}{\sum_{Dj=D\min i}^{D\max i} N(D_0 = D_j)} \qquad (4)$$

Assumption : Poisson Law

$$P(D \ge D_0) = 1 - \exp(-N(D \ge D_0)) \qquad (5)$$

- Global Probability to failure $P(N_f \le N)$ = 10^{-3} (for instance)

For one particle : Two independent events

- initiation of a microcrack at first cycle ($P_{fracture}$, Eq. 2)
- particle diameter D_o large enough for the crack to reach the critical size in N cycles

$$P(N_{prop_particle} \ge N)_{1part} = P\left[\frac{1}{\alpha}\ln(\frac{Df}{D_0}) \ge \frac{1}{\alpha}\ln(\frac{Df}{D})\right] = P(D_0 \le D) \qquad (6)$$

This probability depends on - particle position (surface, subsurface, internal)
- associated volume

PROBABILISTIC MODEL

Global Probability to Failure P (N_f < N) (Ctd)

Can be calculated as a post-processing routine of a FE structural model, with:

- N_{part_s} and N_{el_surf} the number of particles intercepting the element free surface, and the number of elements at the surface of the structure, respectively;
- N_{part_vi} and $N_{el_internal_vol}$ the number of particles contained by the volume of the element, and the number of internal elements of the structure, respectively;
- N_{part_vss} and $N_{el_sub_surface}$ the number of particles contained by the sub-surface volume of the element, and the number of elements at the surface of the structure, respectively.

$$P(Nf \geq N)_{global} =$$

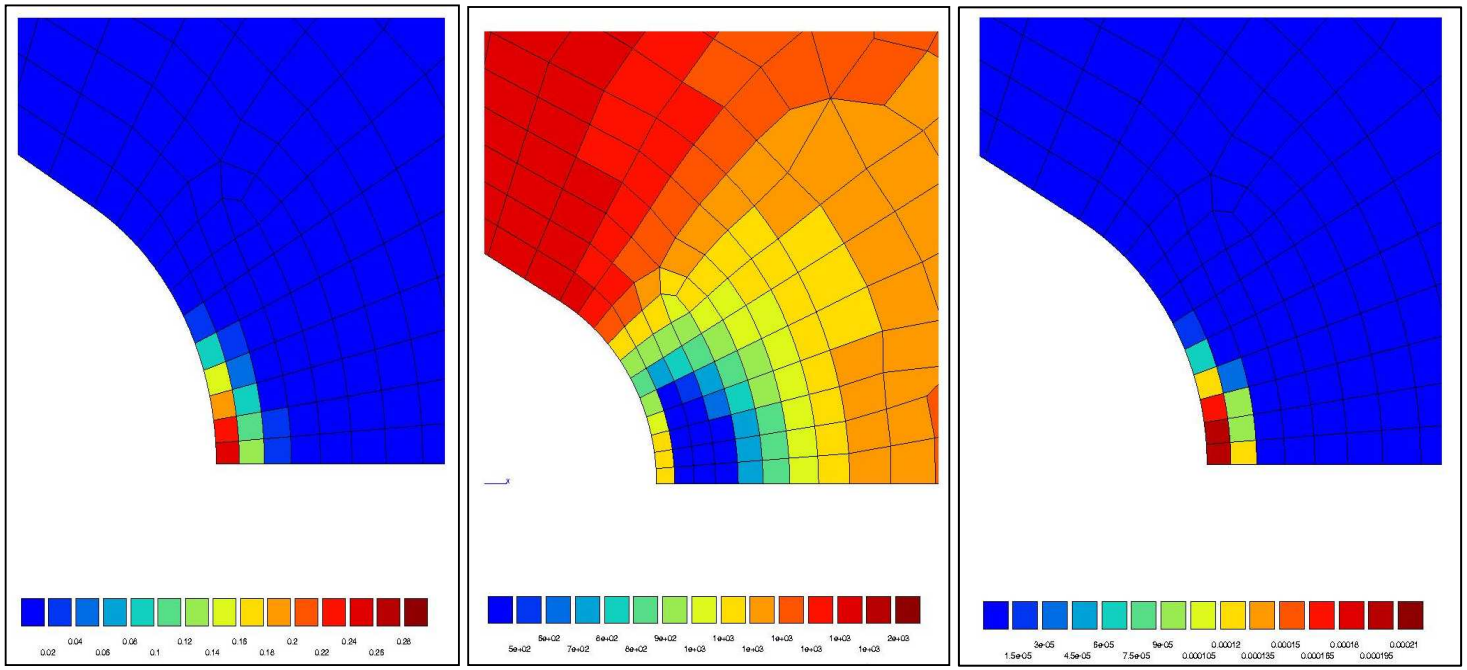
$$1 - \prod_{s=1}^{Nél_surf} \left[\left(1 - P_{fracture}(\sigma_d) * P(D_0 \leq D)\right)^{Npart_s} \right] * \prod_{v=1}^{Nél_internal_vol} \left[\left(1 - P_{fracture}(\sigma_d) * P(D_0 \leq D)\right)^{Npart_vi} \right] \quad (7)$$

$$* \prod_{v=1}^{Nél_sub-surface} \left[\left(1 - P_{fracture}(\sigma_d) * P(D_0 \leq D)\right)^{Npart_vss} \right]$$

WEAKEST LINK THEORY

FINITE ELEMENT ANALYSIS: SHARP NOTCH – INTERMEDIATE LEVEL

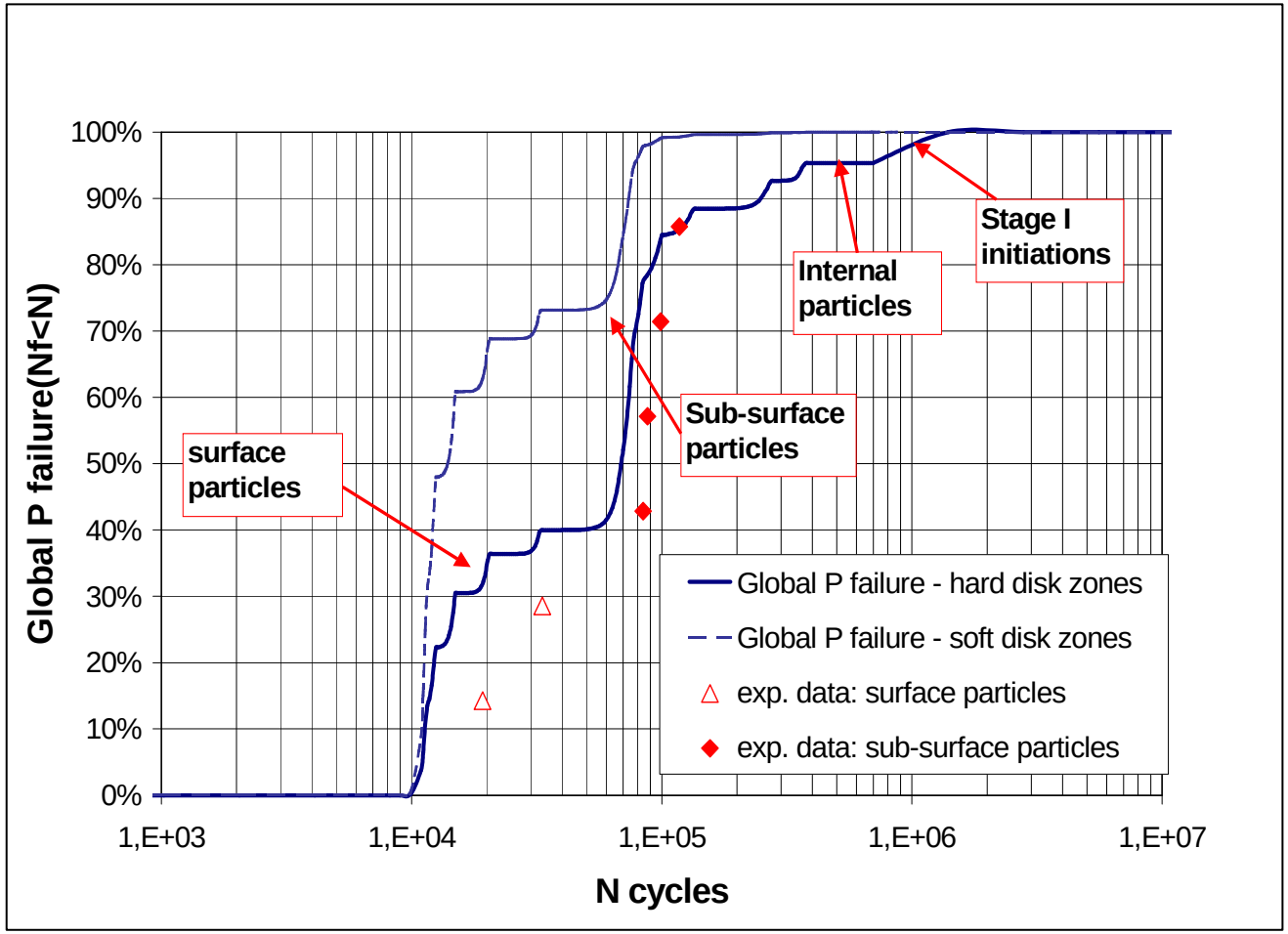
- Identification of (visco)plastic behavior of DA718, mean stress effect accounted for
- 2D models of notched LCF specimens
- Deterministic and probabilistic models programmed as post-processing routine



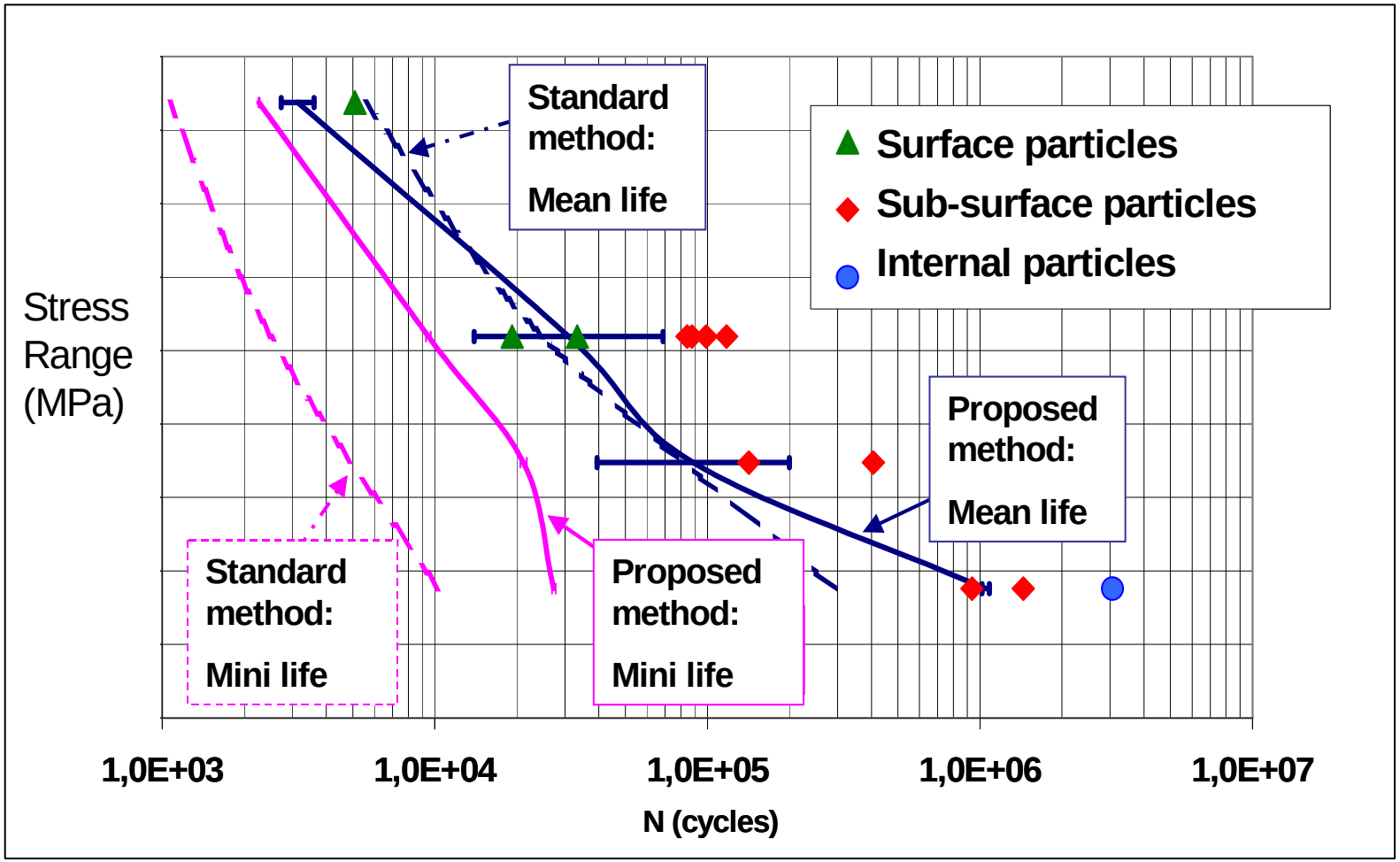
$P_{fracture}$, 1st cycle ***T, stabilized cycle*** ***α, stabilized cycle***

$$da/dN = \alpha(T)\, a$$

LIFE ESTIMATIONS: SHARP NOTCH – INTERMEDIATE LEVEL



LCF CURVES : SHARP NOTCHES



- Good agreement of predicted mean life with experimental results.
- Clear identification of crack initiation sites for a given calculated life.
- Predicted minimum life larger than standard method mini life

ALLOY 718 and OTHER DERIVATIVES BASED ON γ'' PRECIPITATION

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I. INTRODUCTION : Alloys Strengthened by γ'' Precipitates

II. PHYSICAL PROPERTIES OF γ'' PHASE and γ'/γ '' COPRECIPITATES
- II.1. Atomic Structure
- II.2. Composition
- II.3. Dislocations in γ'' phase
- II.4. Compact Morphology
- II.5. γ'' Shape and Coalescence

III. MECHANICAL PROPERTIES OF INCONEL 718 (Introduction)

IV. HIGH TEMPERATURE FATIGUE OF INCONEL 718 in RELATION WITH MICROSTRUCTURE
- Crack Initiation : Grain Size and Initiation from Carbide Particles

V. CONCLUSIONS & PROSPECTS

CONCLUSIONS & PROSPECTS

1. Overview of γ'' strengthened alloys with a special emphasis on Inconel 718
2. Emphasis on microstructure :
   - A_3B Phases (strengthening)
   - NbC & Ti (CN) (fatigue crack initiation sites)
3. Fatigue : Strong environmental effects on crack initiation & crack propagation
4. A new fatigue model allowing
   - description of competition between crack initiation sites in DA 718
   - macroscopic formulation consistent with experimental results
   - easy implementation in a FEM calculation as a post-processor

IMPROVEMENTS

1. Composition & Thermomechanical Heat-Treatments modifications to improve Inconel 718
   - Trace elements : B, P, Mg
   - Al + Ti / Nb
2. Fatigue model
   - Introduction of other probabilistic sources of scatter : Constitution Equations + Stage I crack initiation
   - Full implementation in forging models

THANK YOU

FOR FURTHER INFORMATION

PLEASE CONTACT

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