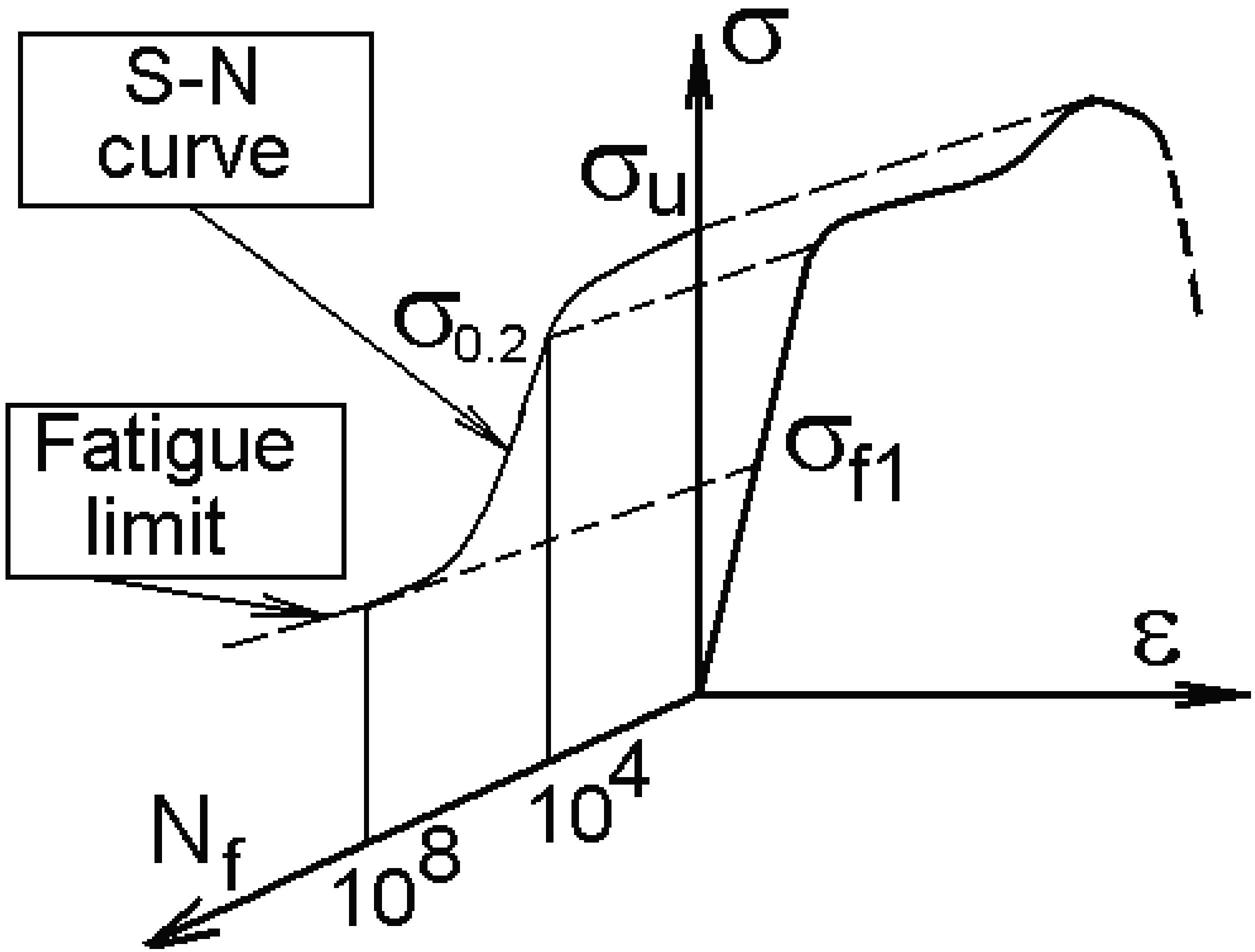

STATE CENTER FOR SAFETY OF CIVIL
AVIATION FLIGHTS
Moscow, Russia

Synergetics of in-service titanium alloys fatigue cracking.

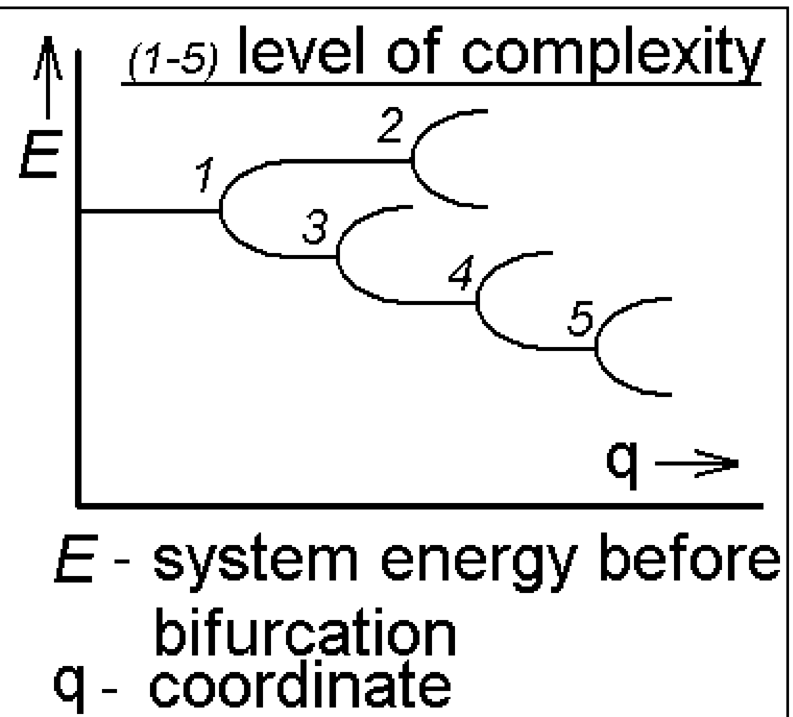
A.Shanyavsky,

State Center for Civil Aviation Flights Safety, Russia.

Wöhler's fatigue S-N curve constructed based on the tension diagram for metals.

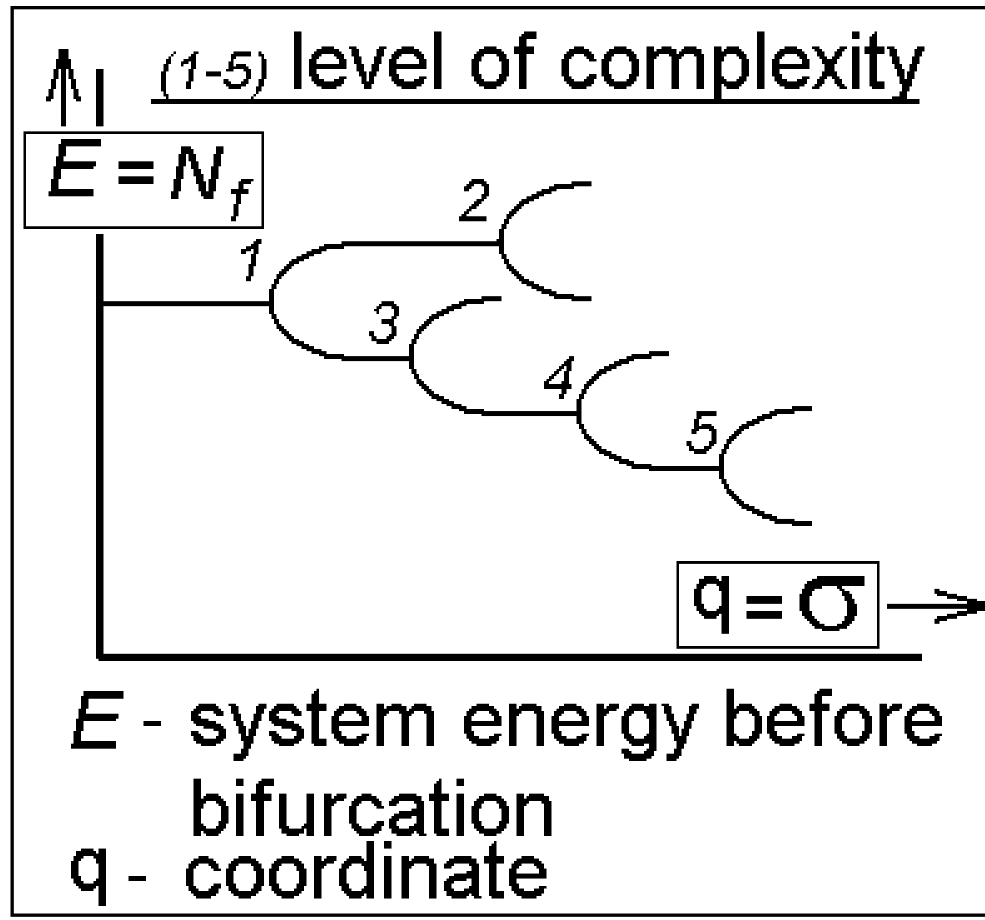


The cascade (a) of bifurcation transitions in behaviour of evaluated an open synergetic systems is describing as «Kelly's tree», and (b) the schema of the cascade of changes in behaviour of metals in process of increase of cyclic stress level.



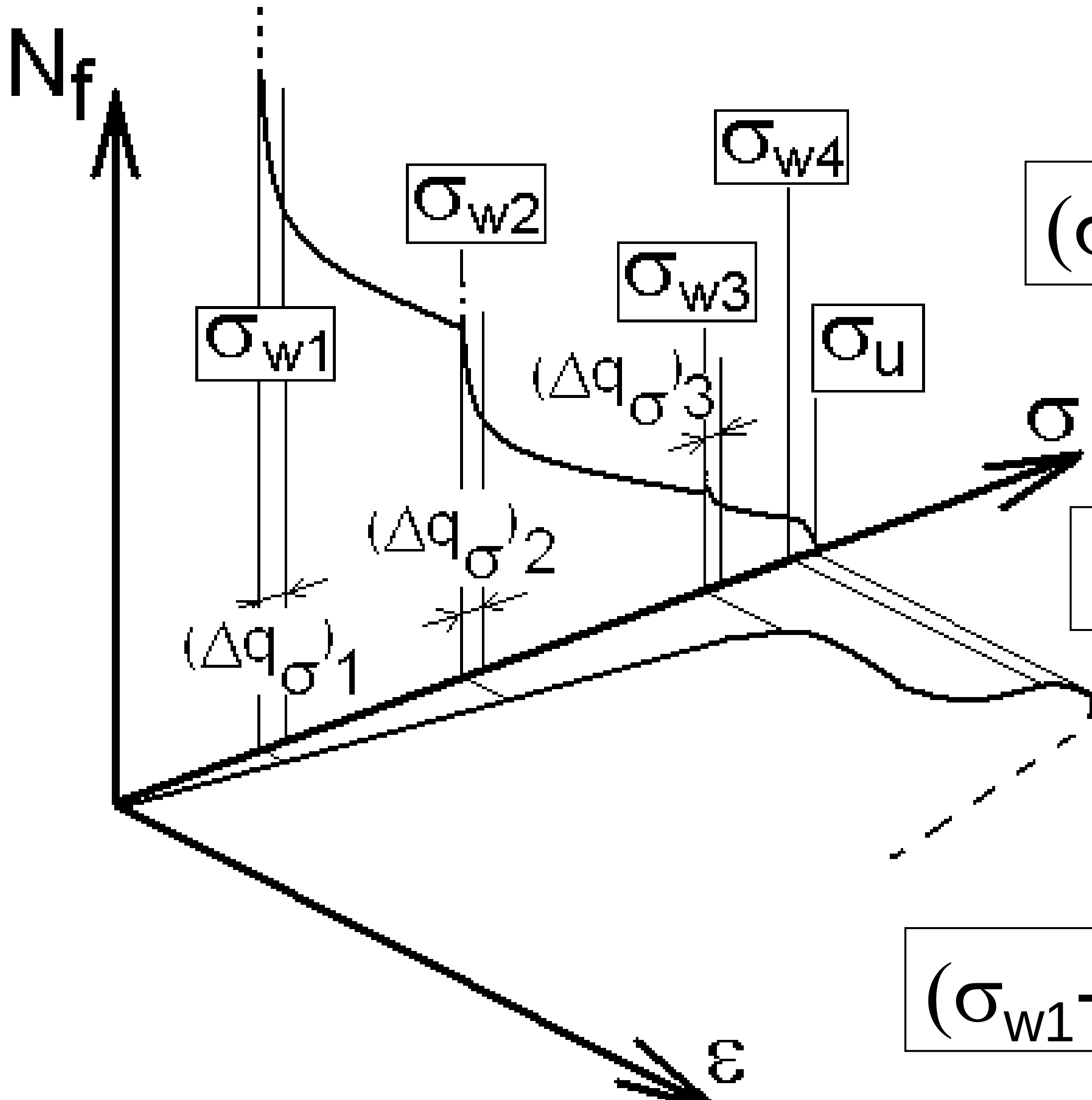
a)

b)



BIFURCATION DIAGRAM FOR FATIGUED METALS

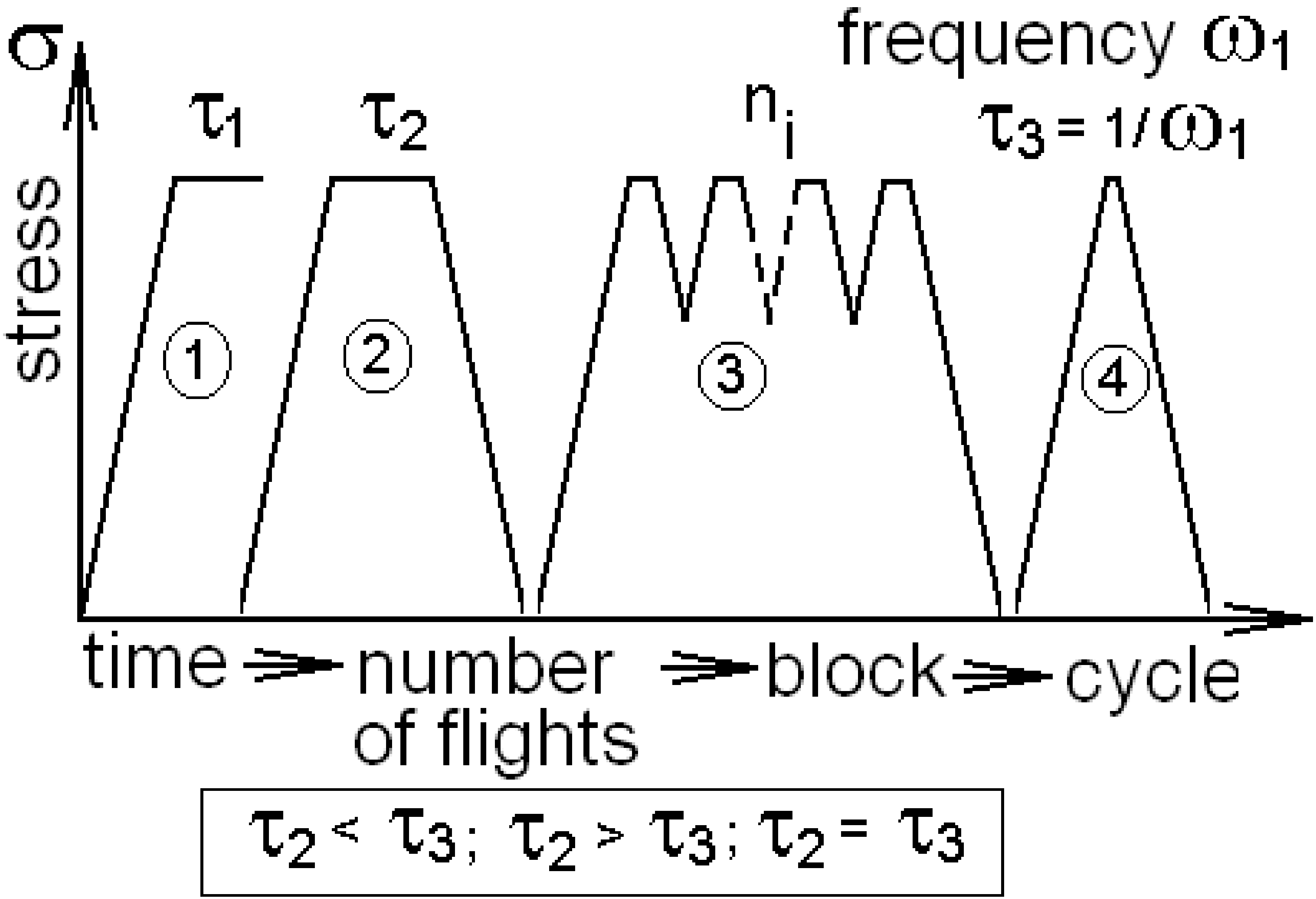
(A.A.SHANYAVSKIY,2003)



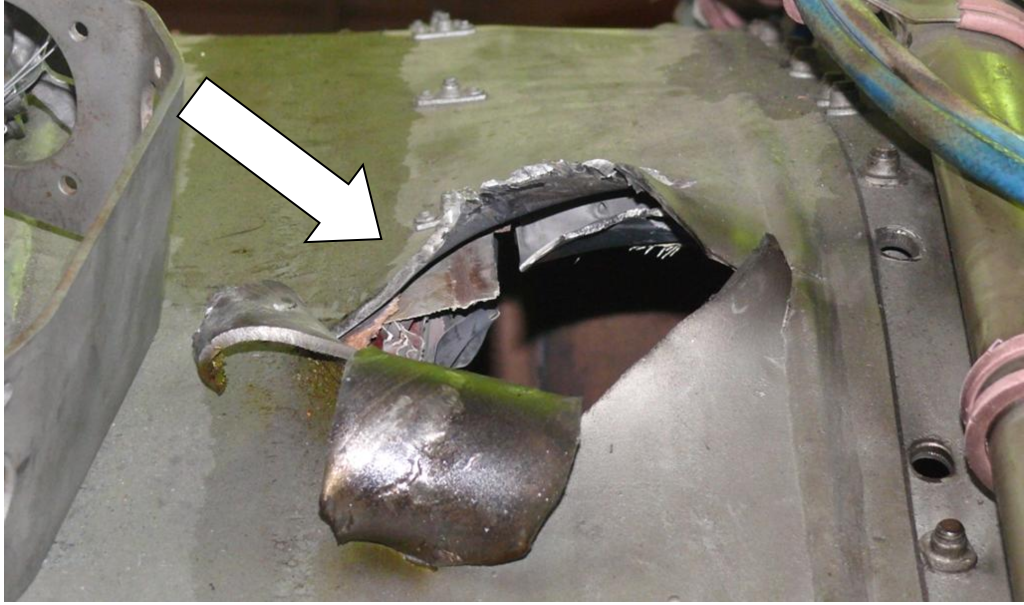
$(\sigma_{w3}$-$\sigma_{w4})$-HCF

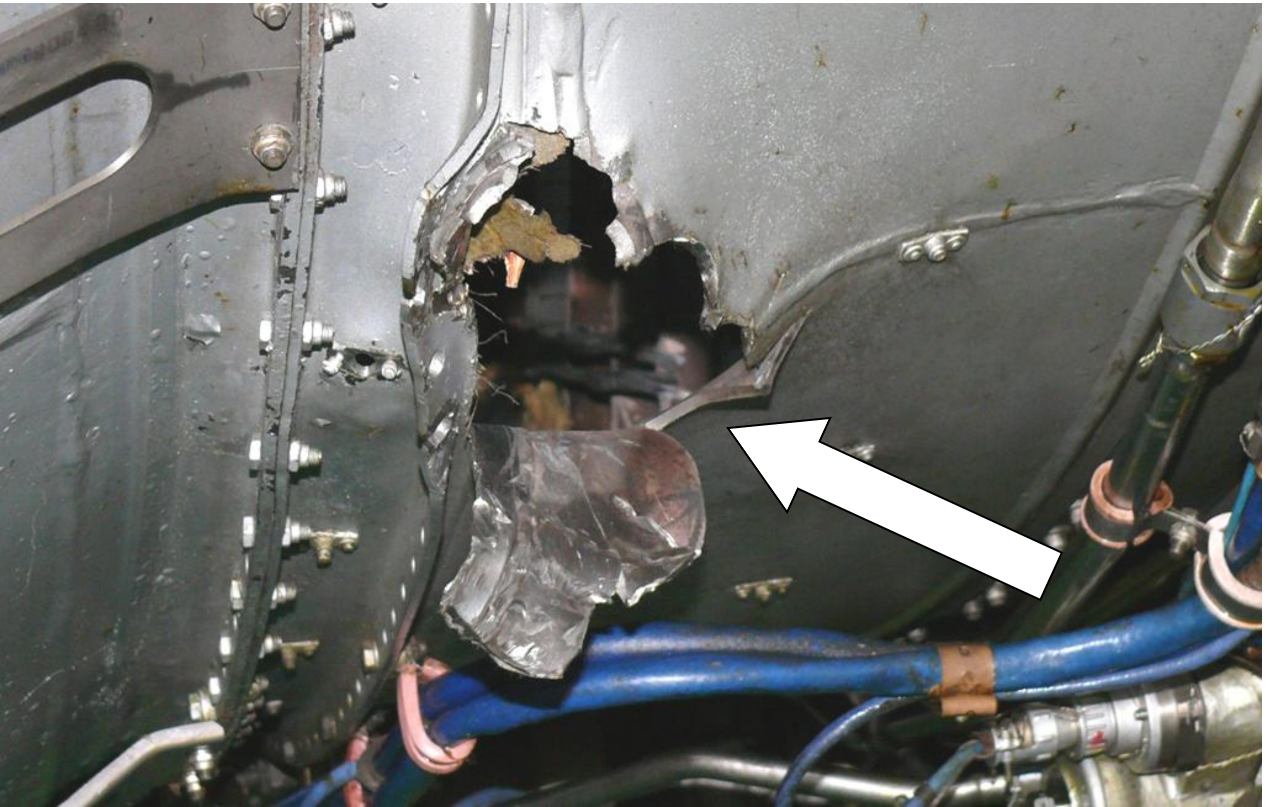
$(\sigma_{w2}$-$\sigma_{w3})$-HCF

$(\sigma_{w1}$-$\sigma_{w2})$-VHCF

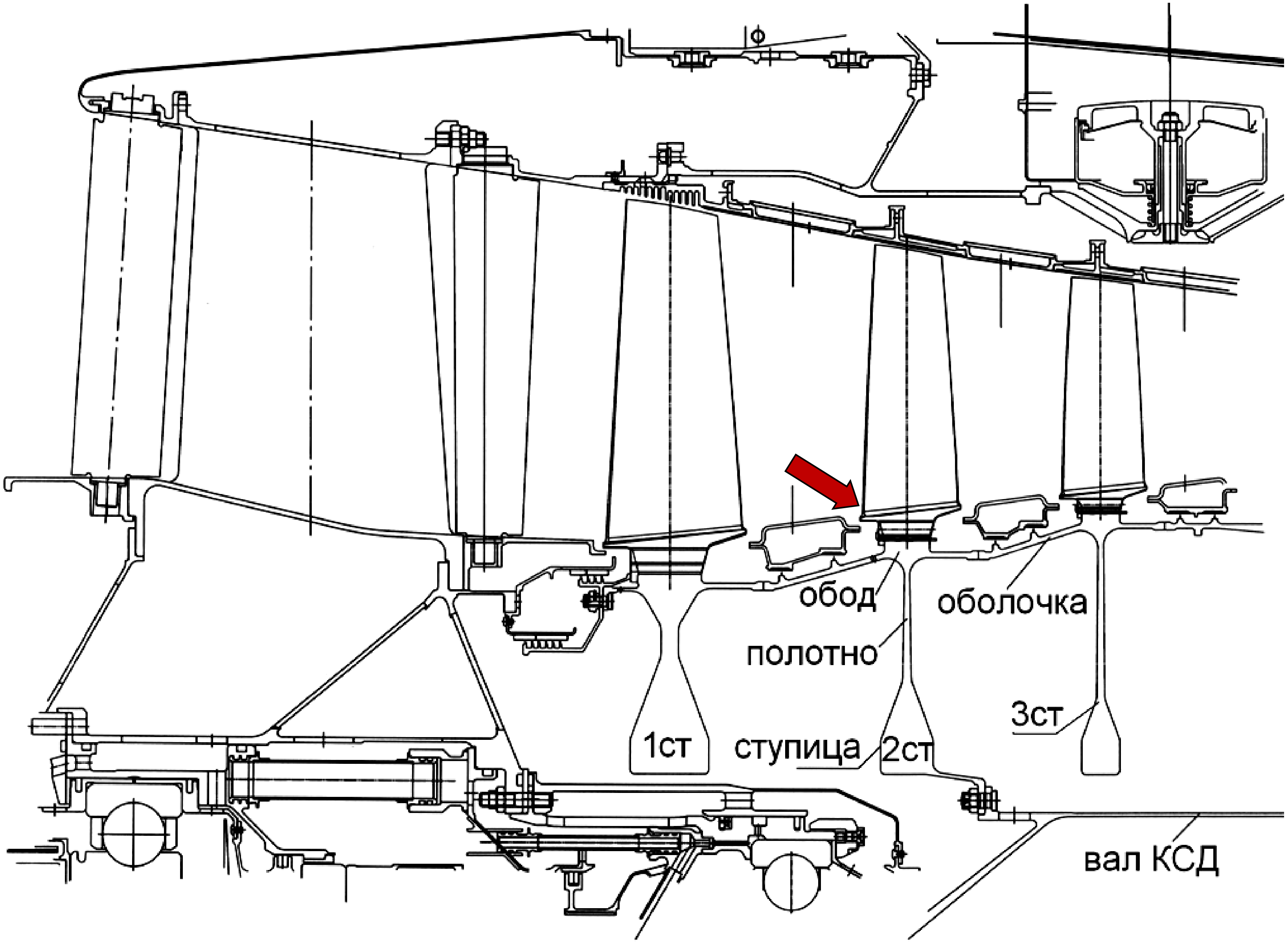

σ
stress
τ1
τ2
n_i
frequency ω1
τ3 = 1/ω1
1
2
3
4
time
number of flights
block
cycle
τ2 < τ3; τ2 > τ3; τ2 = τ3

Out-site overview of non-localized failure areas (shown by arrows) of the engine D-18T casing due to parts of in-flight went-out fragmented rim of the titanium disk of the LPC second stage (June 2010).



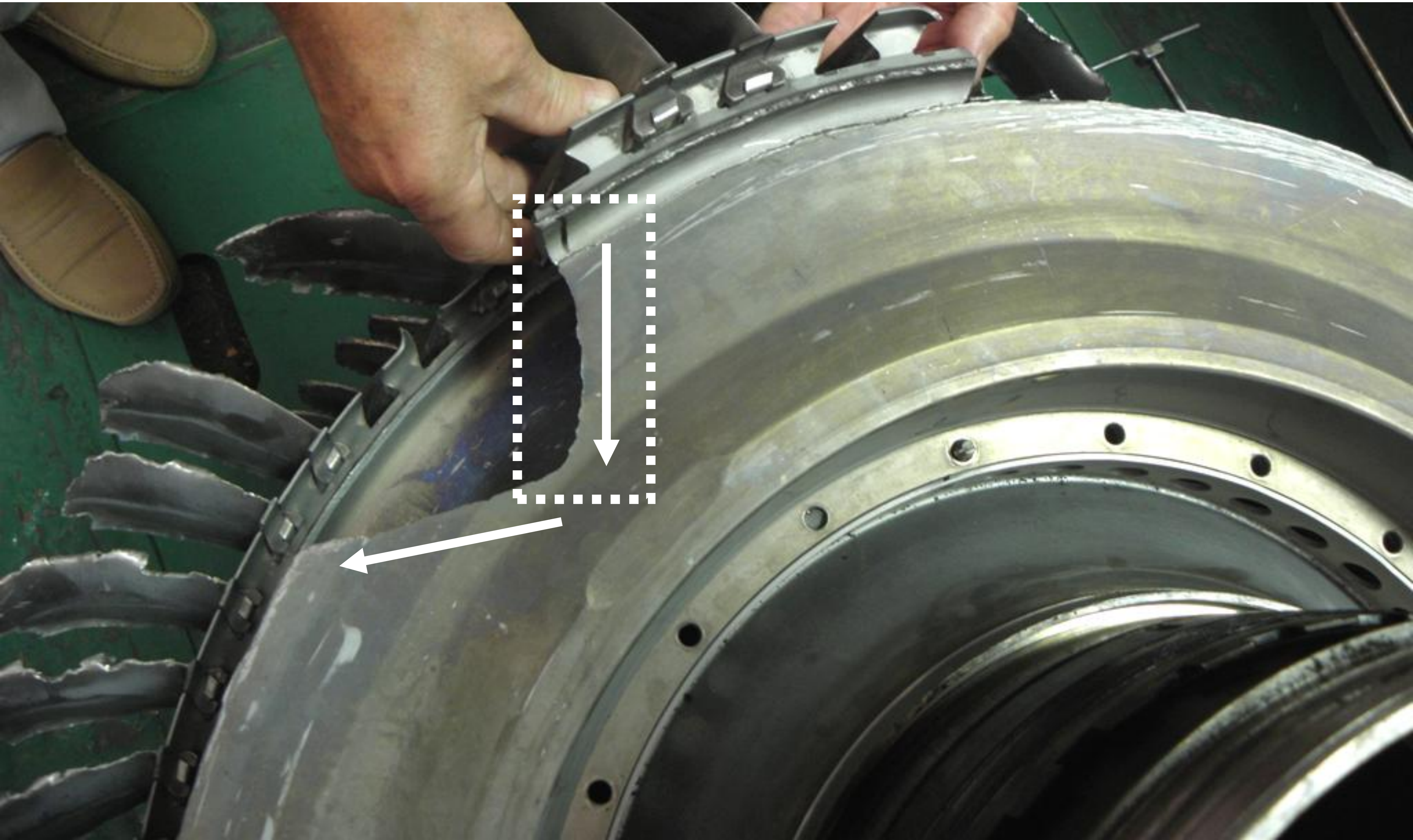


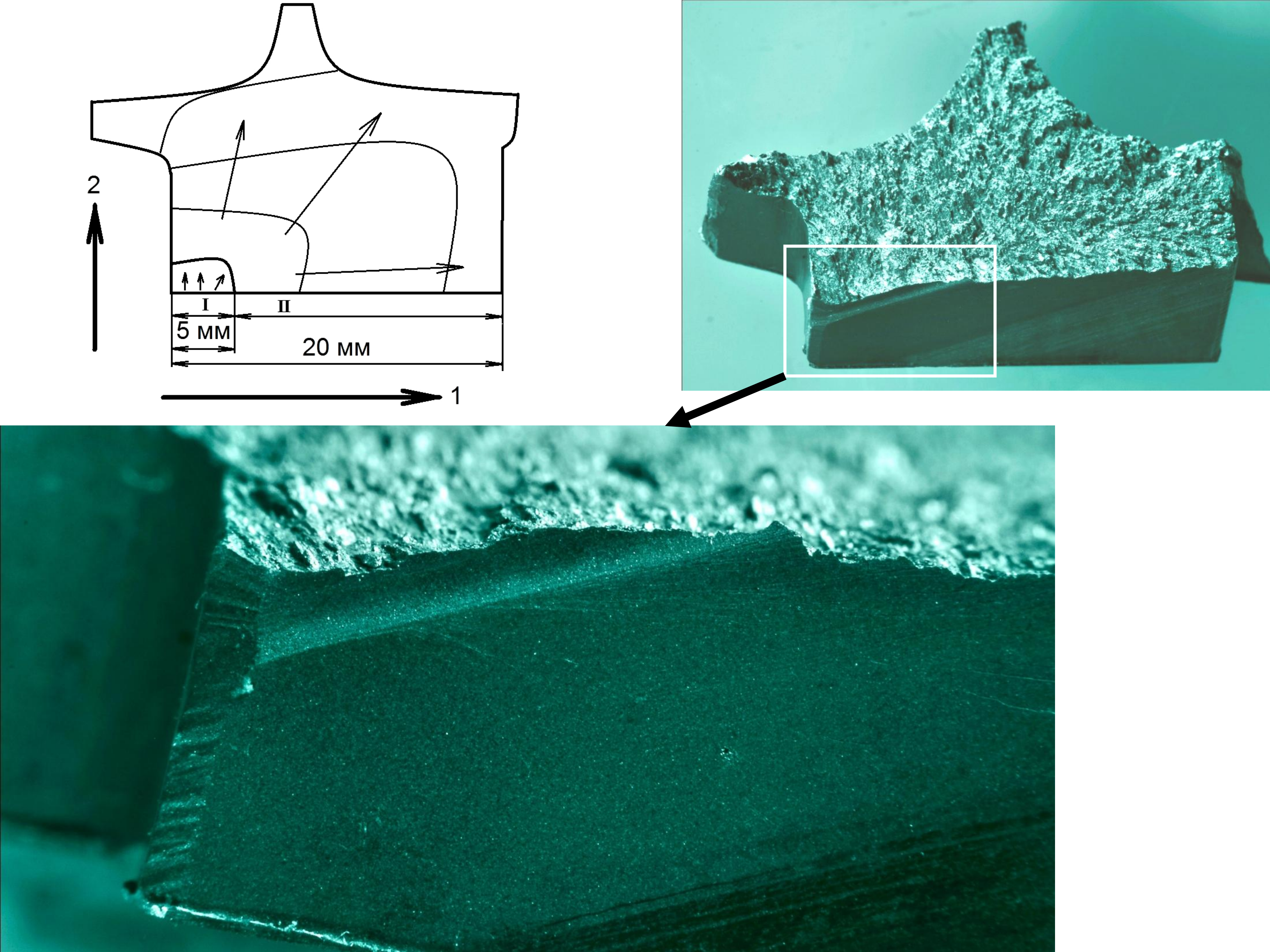
Schema of several LPC stages of aircraft engine D-18T.
The red arrow pointed out area of the second stage LPC cracking.



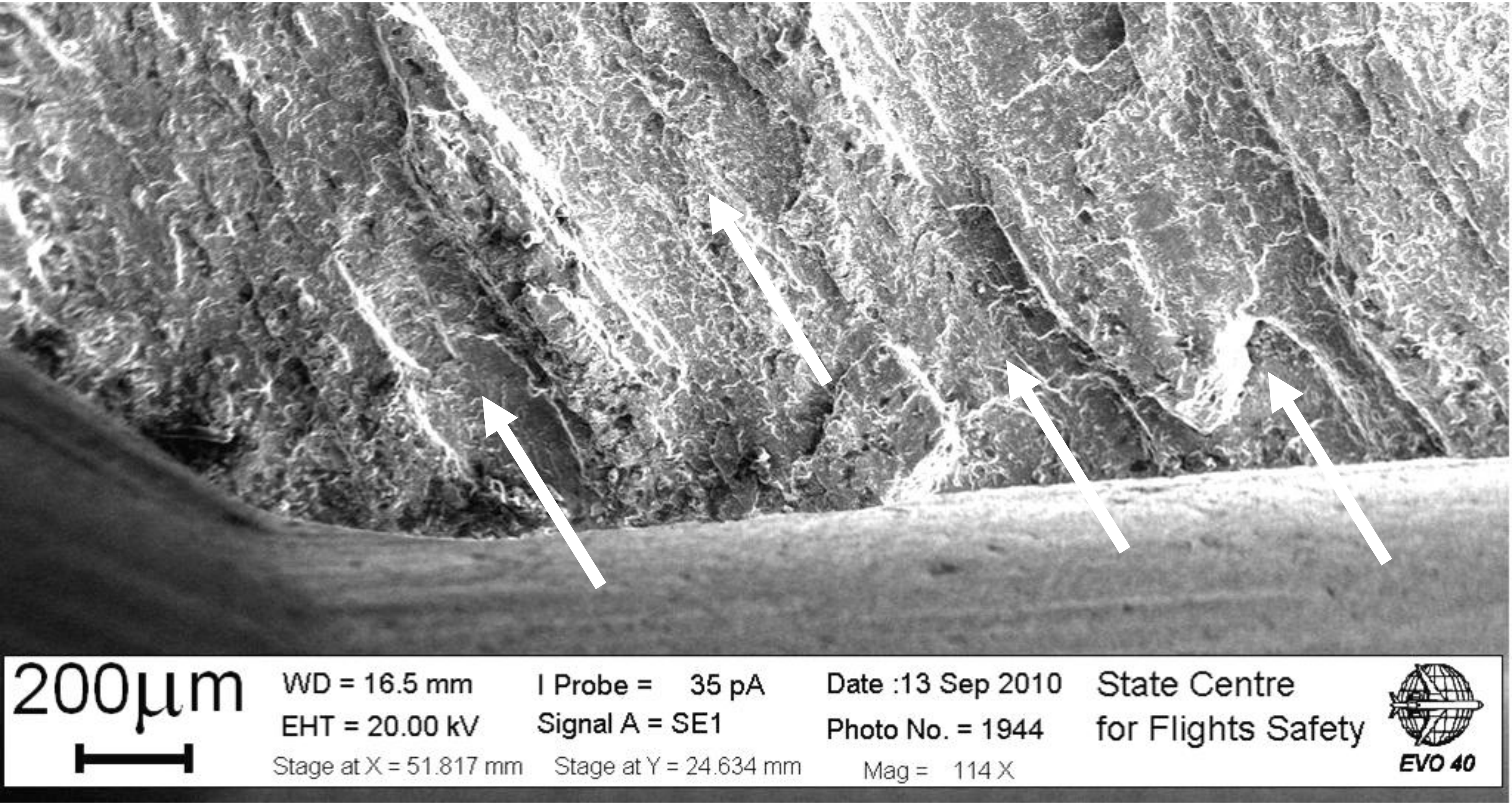
Overview of several connected fragments (shown by arrows) of the failed titanium disk rim of the second stage LPC with several crashed blades

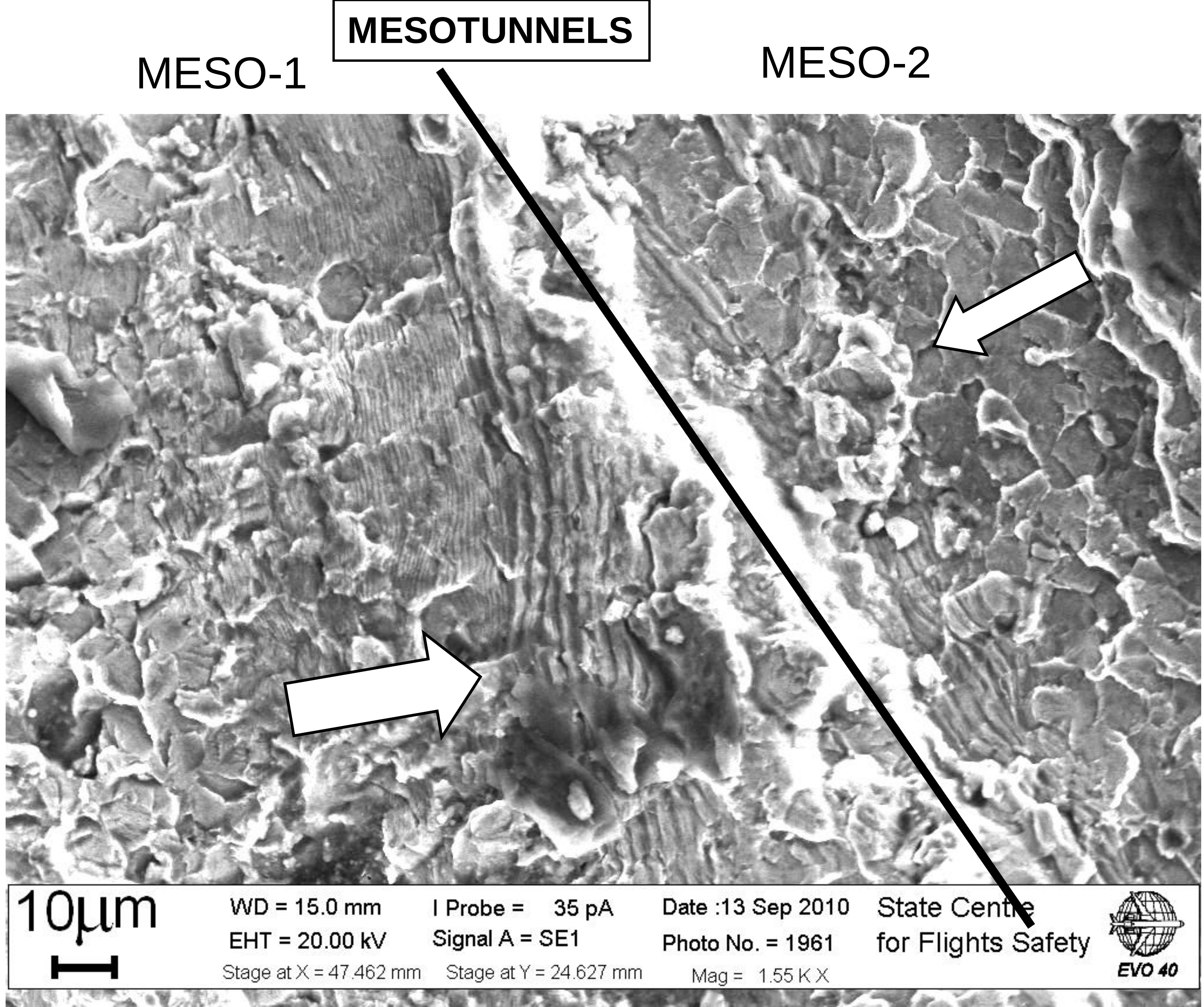
AREA OF THE FIRST STEP OF TITANIUM DISK CRACKING

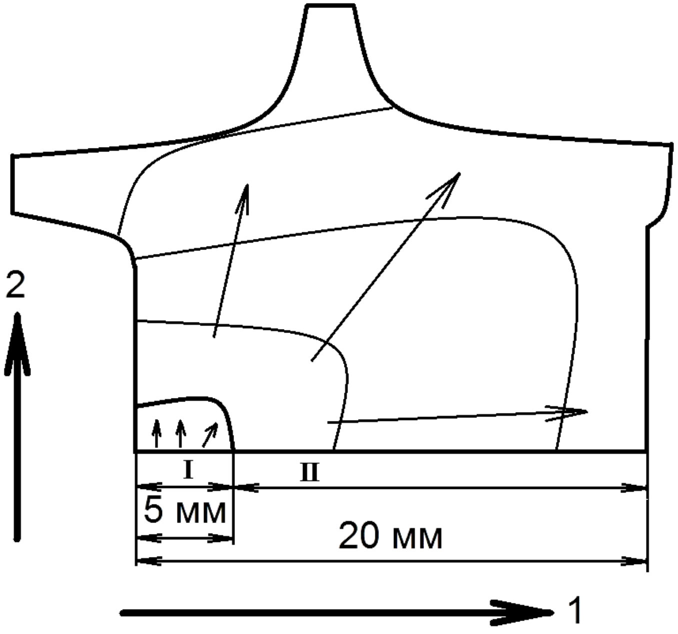



2
I
II
5 мм
20 мм
1

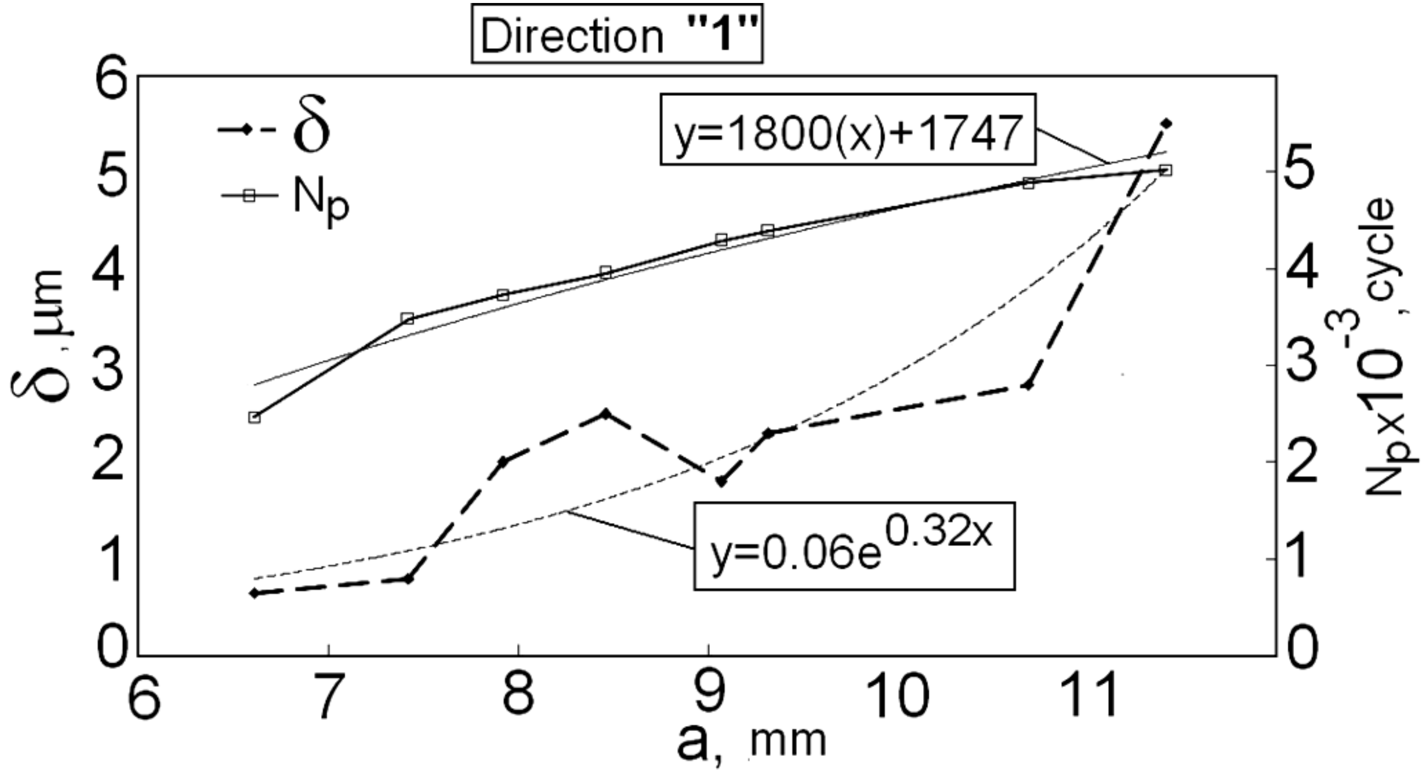
MESOTUNNELS FOR FATIGUED DISK IN LCF REGIME



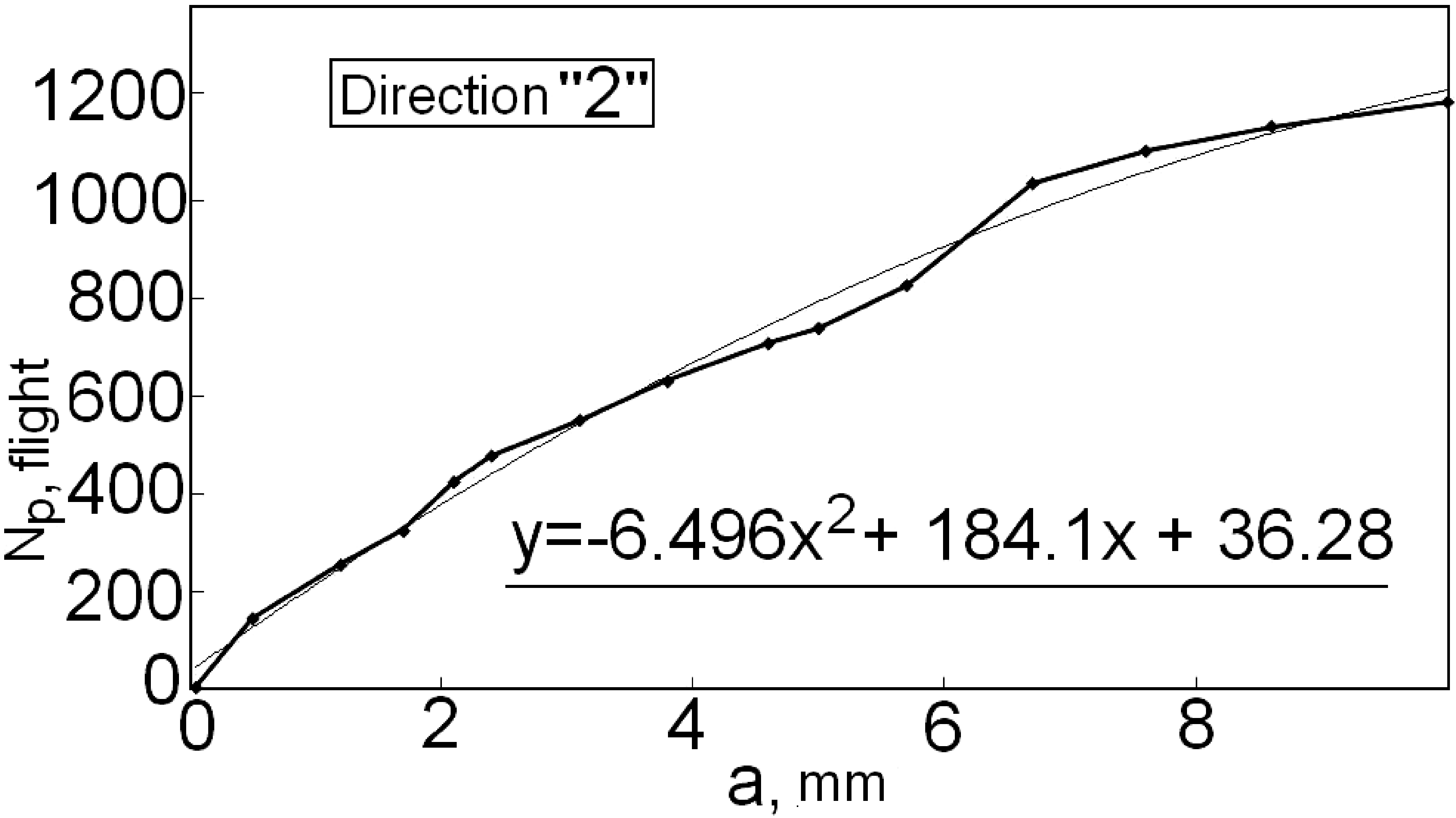

MESOTUNNELS
MESO-1
MESO-2
10µm
WD = 15.0 mm
EHT = 20.00 kV
I Probe = 35 pA
Signal A = SE1
Date :13 Sep 2010
Photo No. = 1961
State Centre
for Flights Safety
Stage at X = 47.462 mm
Stage at Y = 24.627 mm
Mag = 1.55 K X
EVO 40



NUMBER OF CYCLES HAS BEEN DETERMINED BASED ON FATIGUE STRIATIONS COUNTING



NUMBER OF FLIGHTS HAVE BEEN ESTIMATED WITH DECREASING NUMBER OF STRIATIONS ON FACTOR 8.0



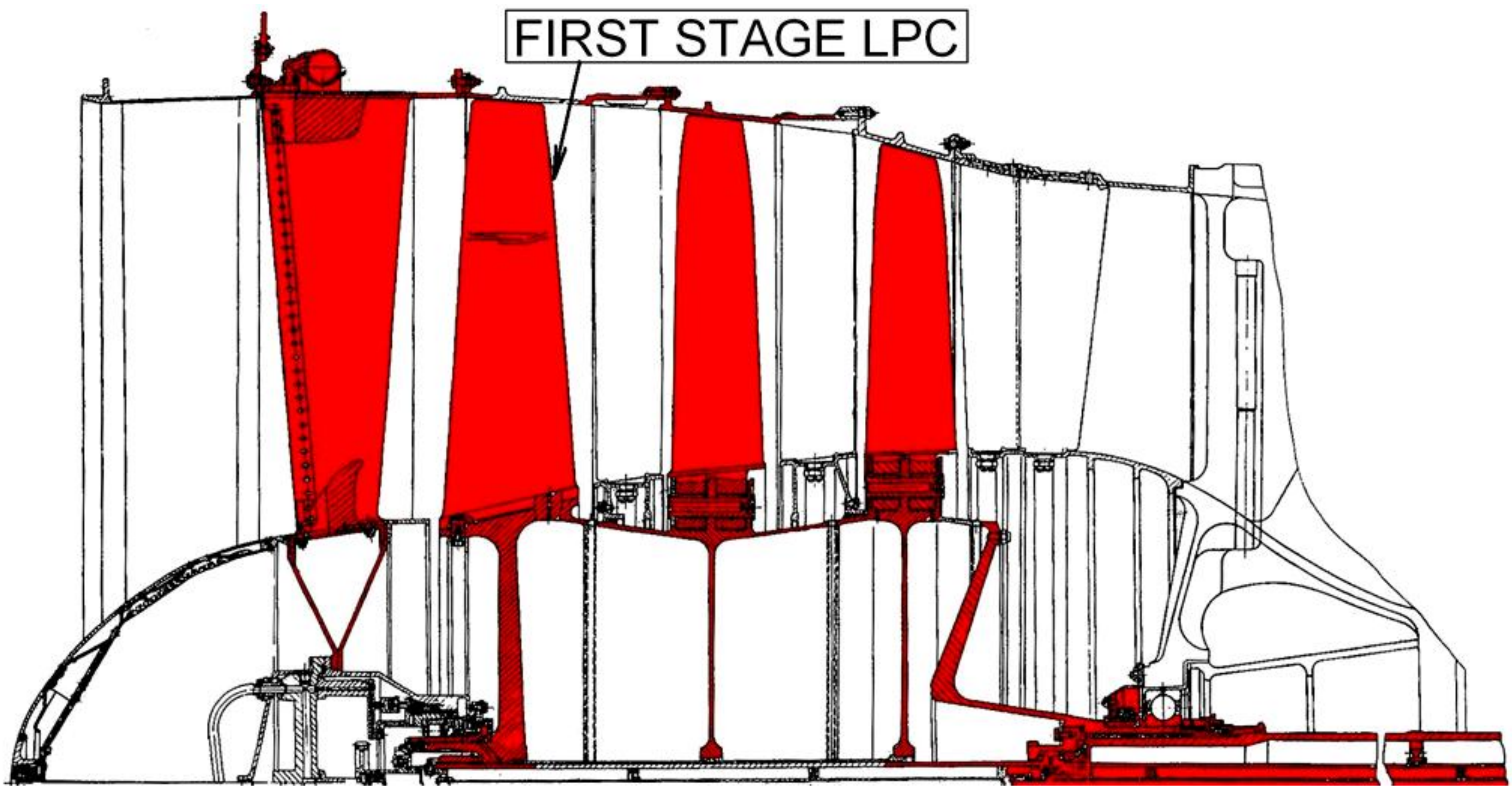
CONCLUSION

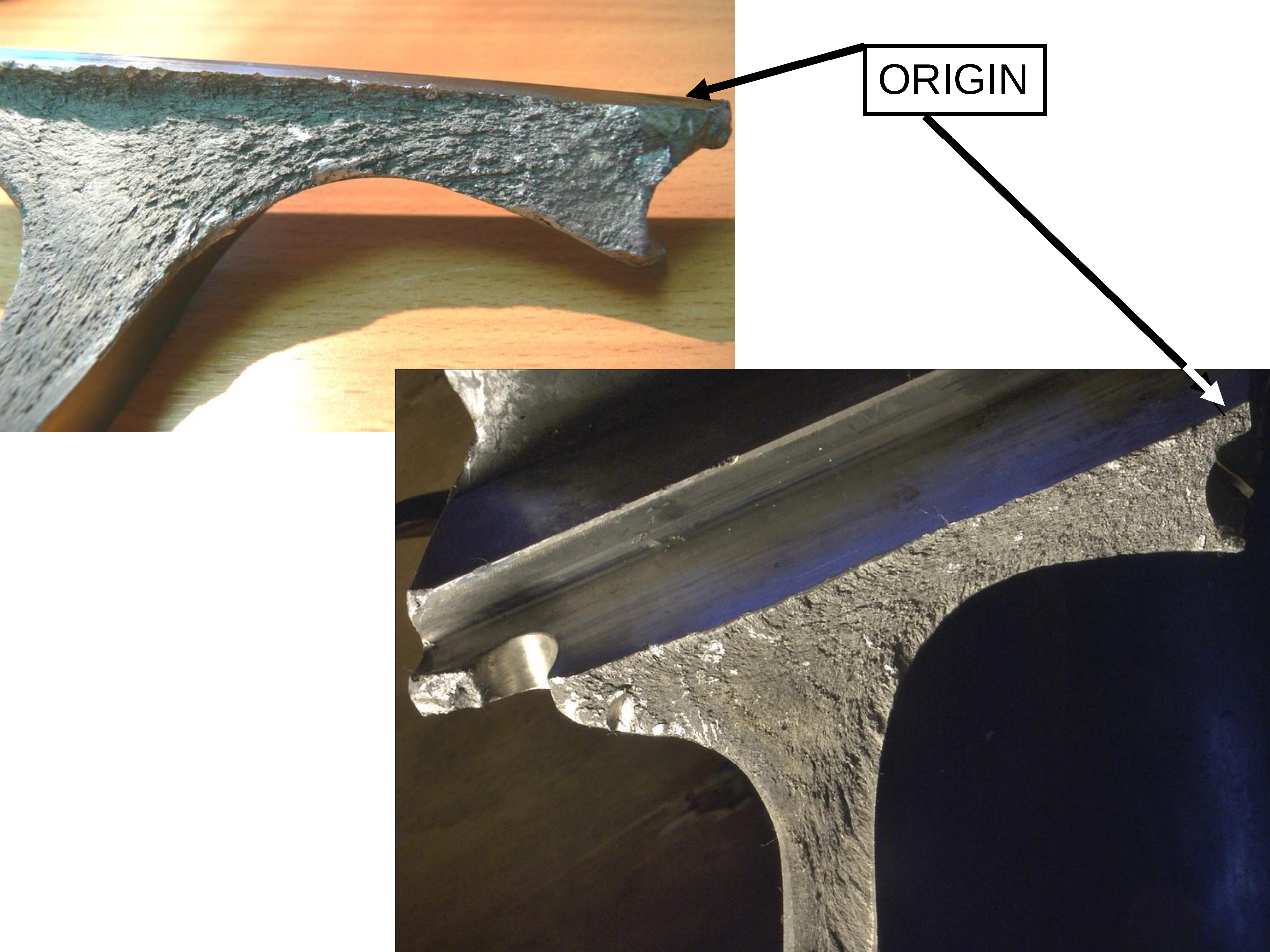
BECAUSE OF ***<u>LCF</u>*** HAS TAKEN PLACE FOR TITANIUM DISKS, NON-DESTRUCTIVE INSPECTION ALL FLEET TITANIUM DISKS OF THE SAME TYPE
WITH INTERVAL ***<u>200 FLIGHTS</u>***
CAN BE INTRODUCED FOR RELAIBLE
AND SAFETY AIRCRAFT FLIGHTS

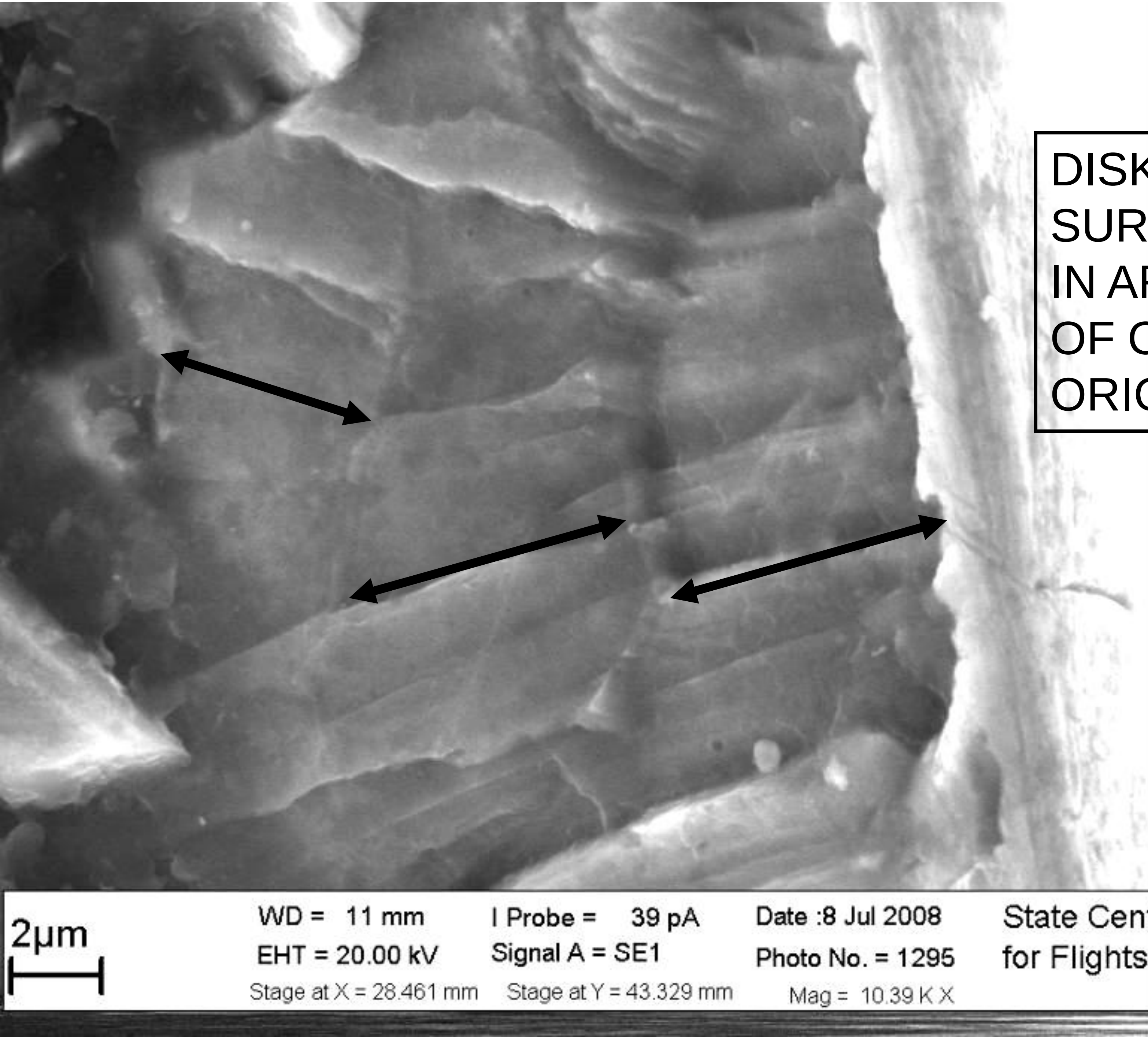
TITANIUM DISKS FAILURES
IN ***<u>HCF-LCF</u>*** REGIME; ENGINE D-30KU

NUMBER OF FLIGHTS: No1 – 1000;
No2 – 6100;
No3 - 9700

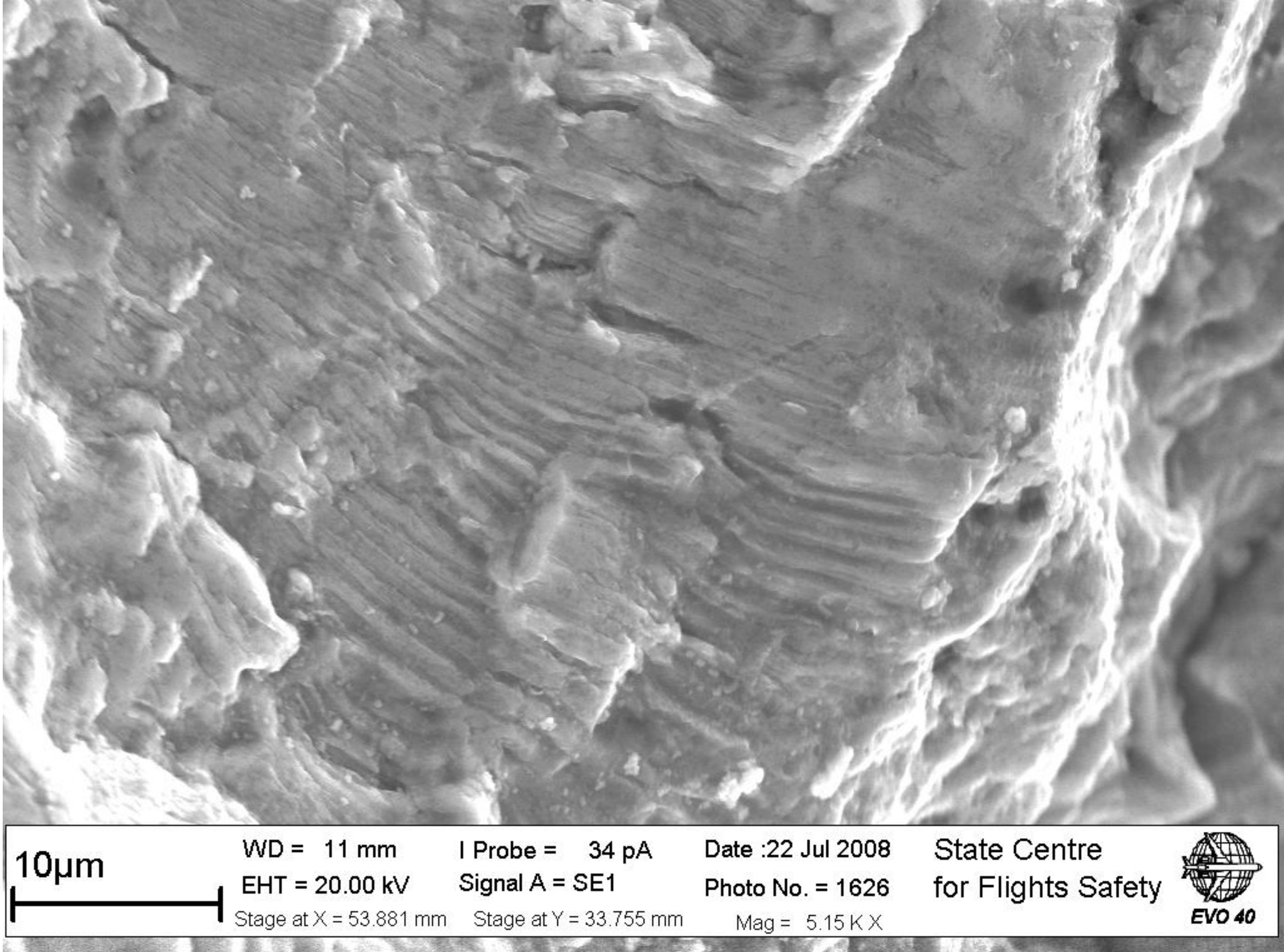
AIRCRAFT ENGINE D-30KU-154 FOR THE AIRCRAFT TU-154B



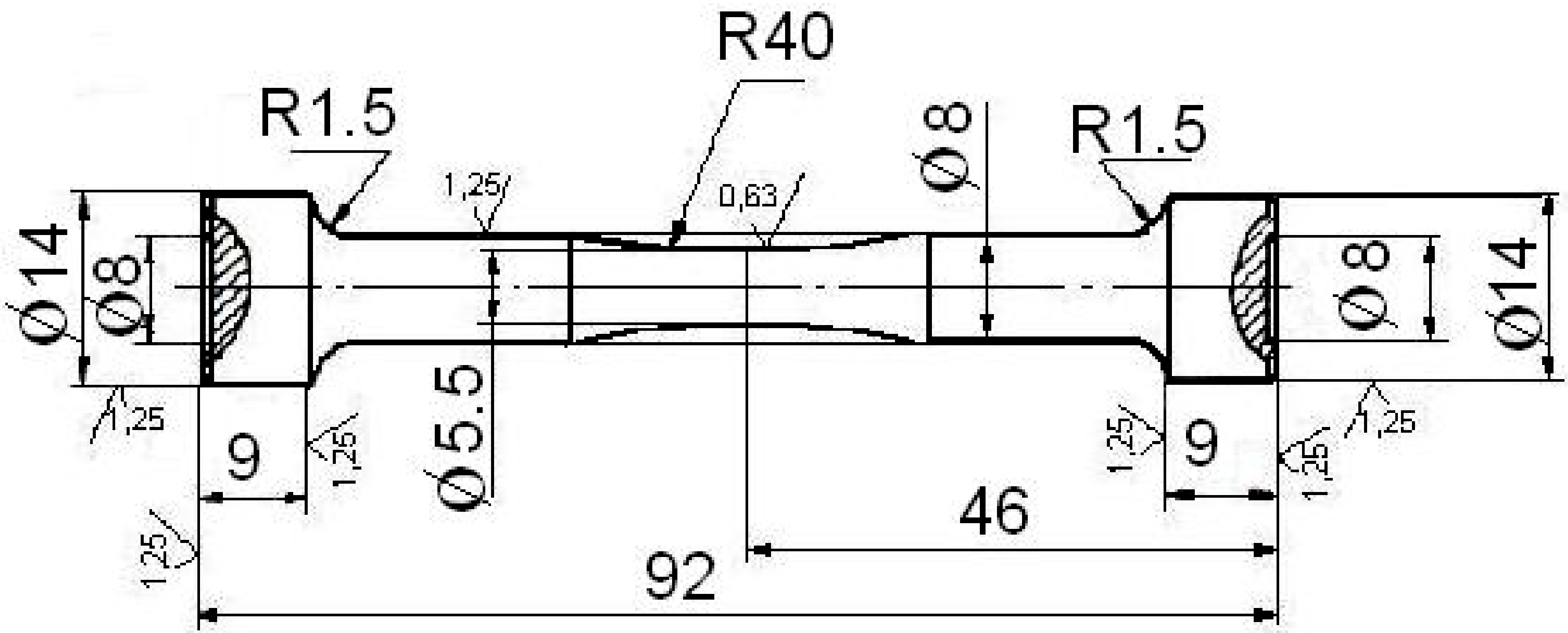

ORIGIN



DISK No2
SURFACE
IN AREA
OF CRACK
ORIGINATION


10µm
WD = 11 mm
EHT = 20.00 kV
Stage at X = 53.881 mm
I Probe = 34 pA
Signal A = SE1
Stage at Y = 33.755 mm
Date :22 Jul 2008
Photo No. = 1626
Mag = 5.15 K X
State Centre
for Flights Safety
EVO 40

Shape of smooth specimens used in fatigue tests of titanium alloy VT3-1

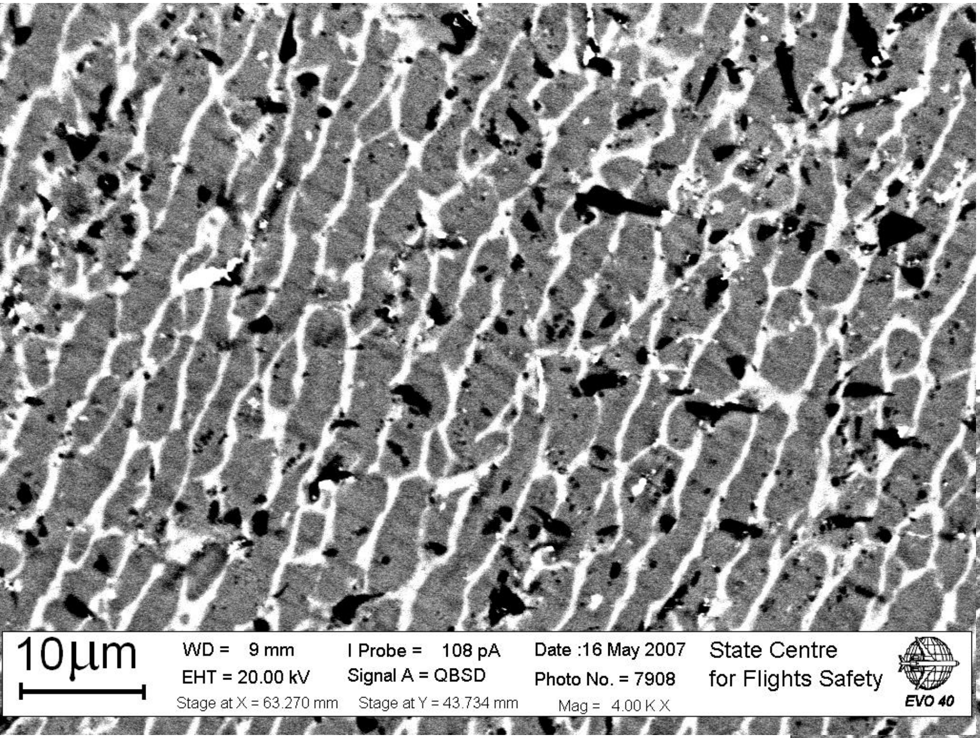


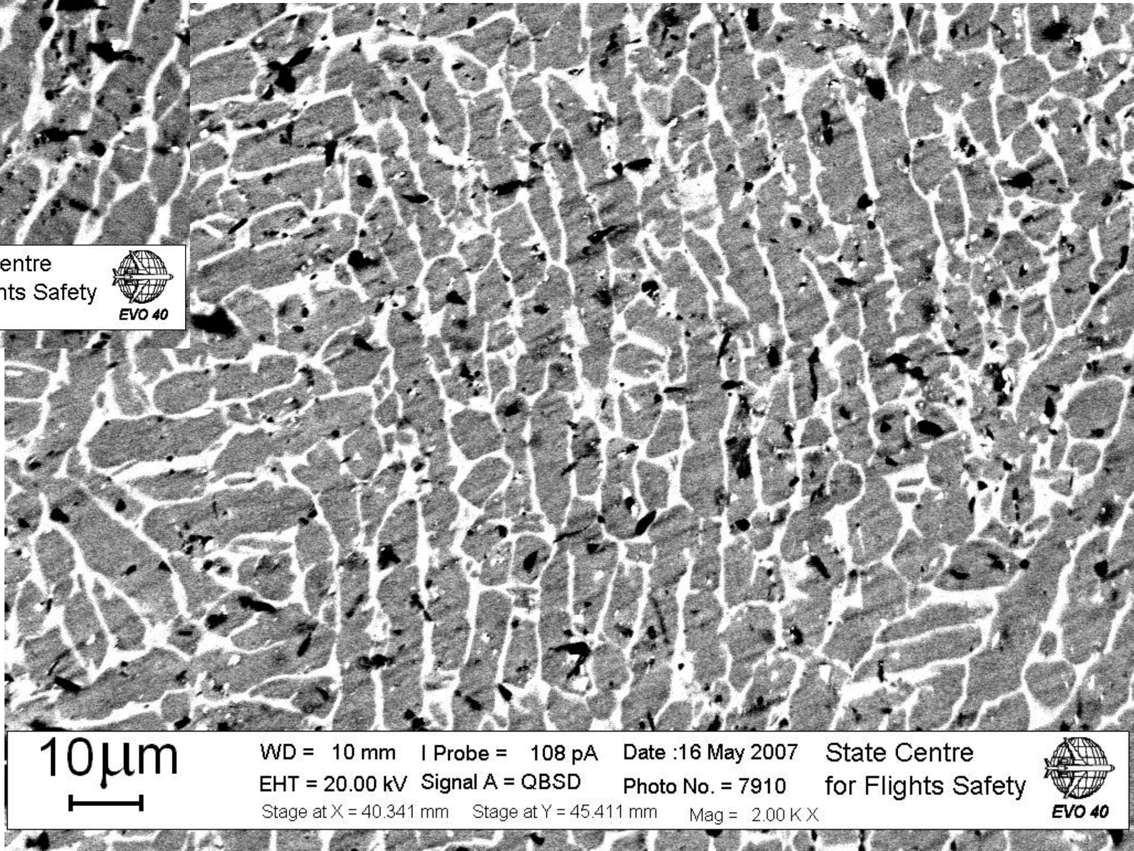
Mechanical properties and material composition of the investigated titanium alloy VT3-1

Ultimate tensile stress - 1200-1400 MPa;
Yield stress – 1000-1200 MPa.
Elongation – 20-30%

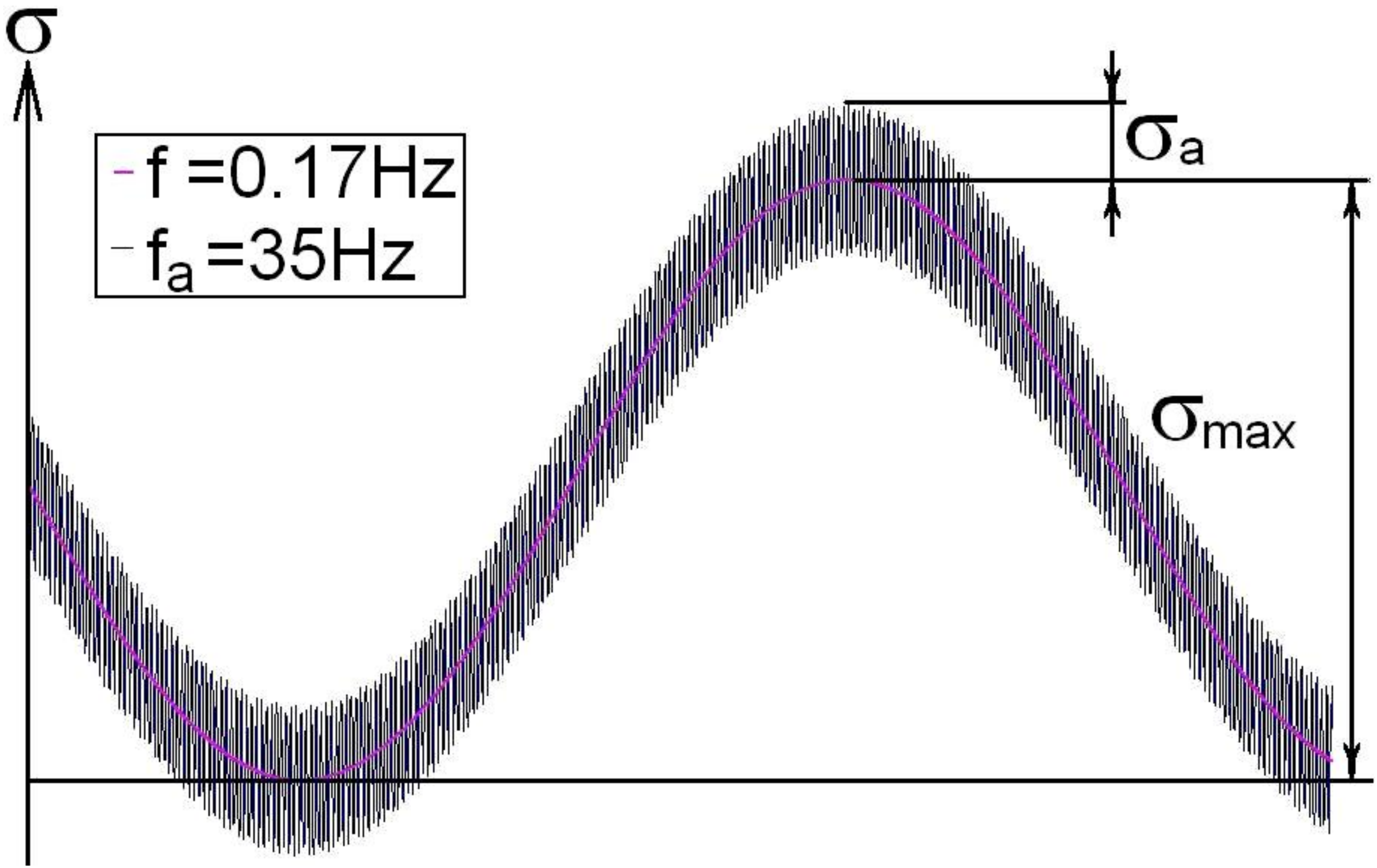
Material composition (wt%)									
Ti	Al	Mo	Zr	Si	C	Fe	O_2	N_2	H_2
Remain-der	5.8-7.0	2.8-3.8	0.8-2.5	0.2-0.35	≤0.1	≤0.25	≤0.15	≤0.05	≤0.015

Overview of material structures of the investigated bi-phase ($\alpha+\beta$) Ti-alloy



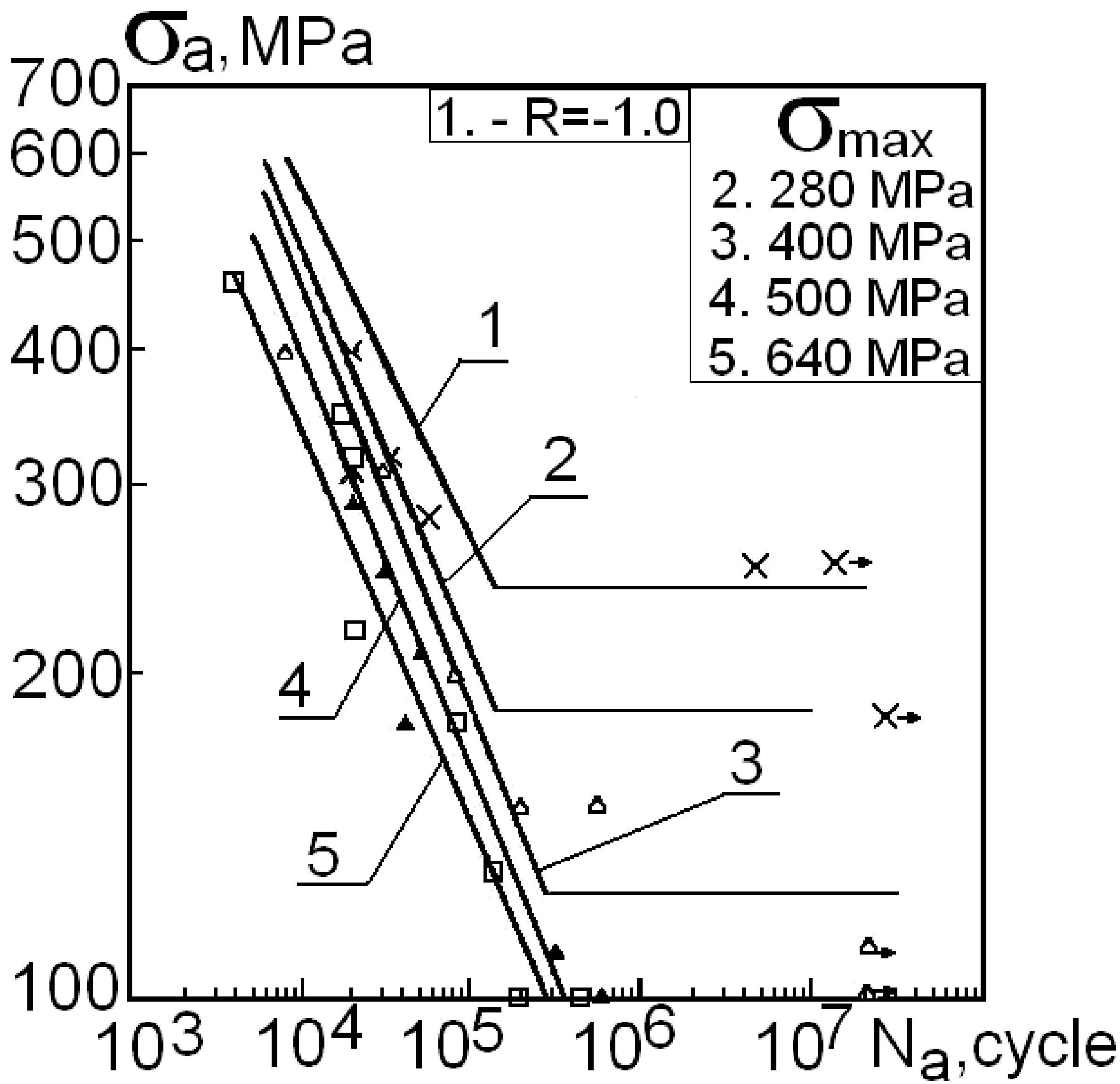


Schema of bi-modal cyclic loads used in fatigue tests for specimens of investigated Ti-6Al-3Mo-0.4Si alloy

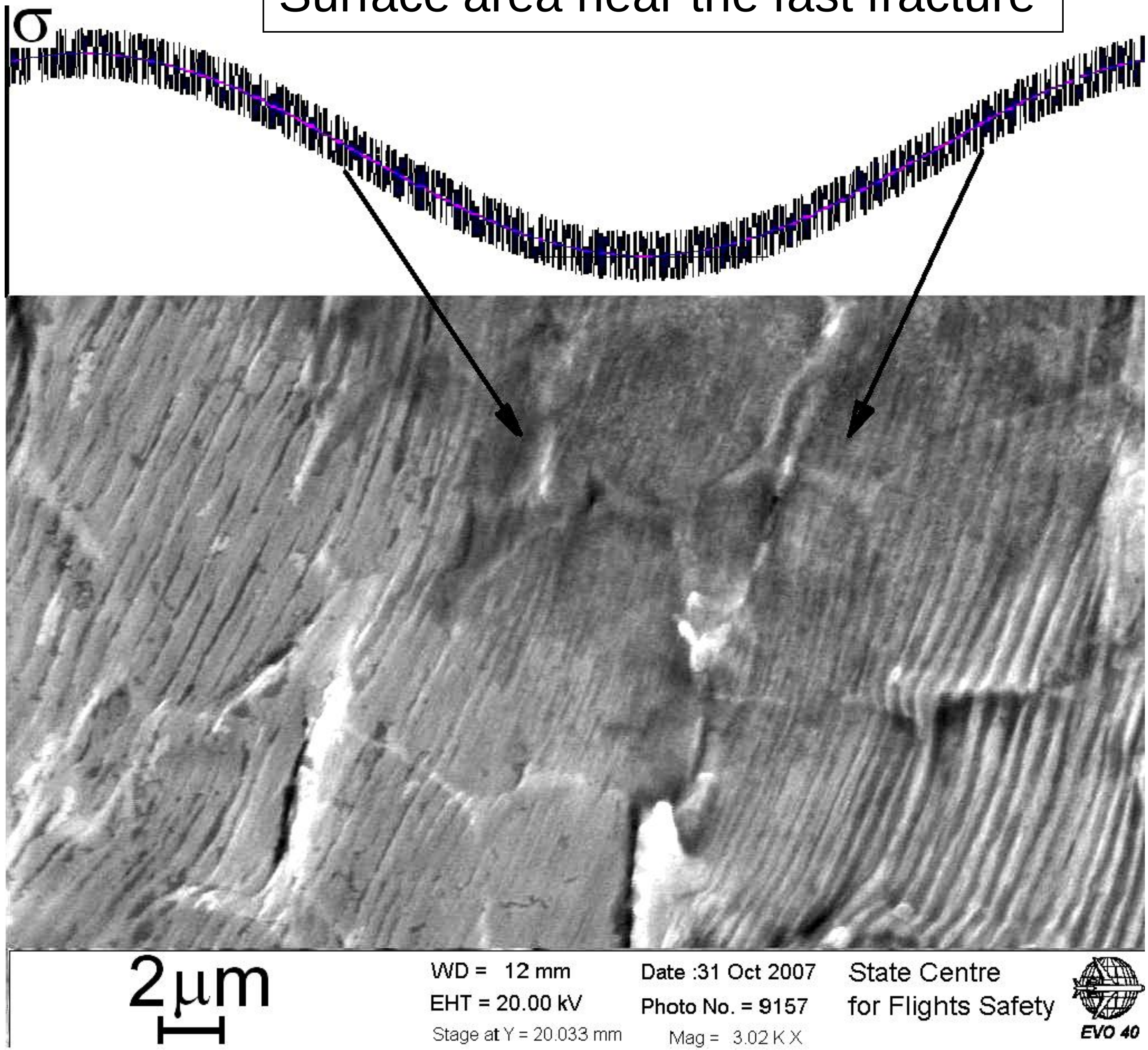


nn	σ_{Max}, MPa	N_{max}, cycle	σ_a, MPa	N_a, cycle
1	640	945	100	187650
2	640	682	130	135525
3	640	105	320	20850
4	640	105	320	20850
5	640	94.5	350	18765
6	640	21	460	4100
7	640	21	460	4170
8	500	1606	110	319005
9	500	260	210	52125
10	500	260	210	52125
11	500	105	290	20850
12	500	105	310	20850
13	400	2835	150	562950
14	400	420	200	83400
15	400	158	310	31275
16	400	42	400	8340
17	280	105	400	20850

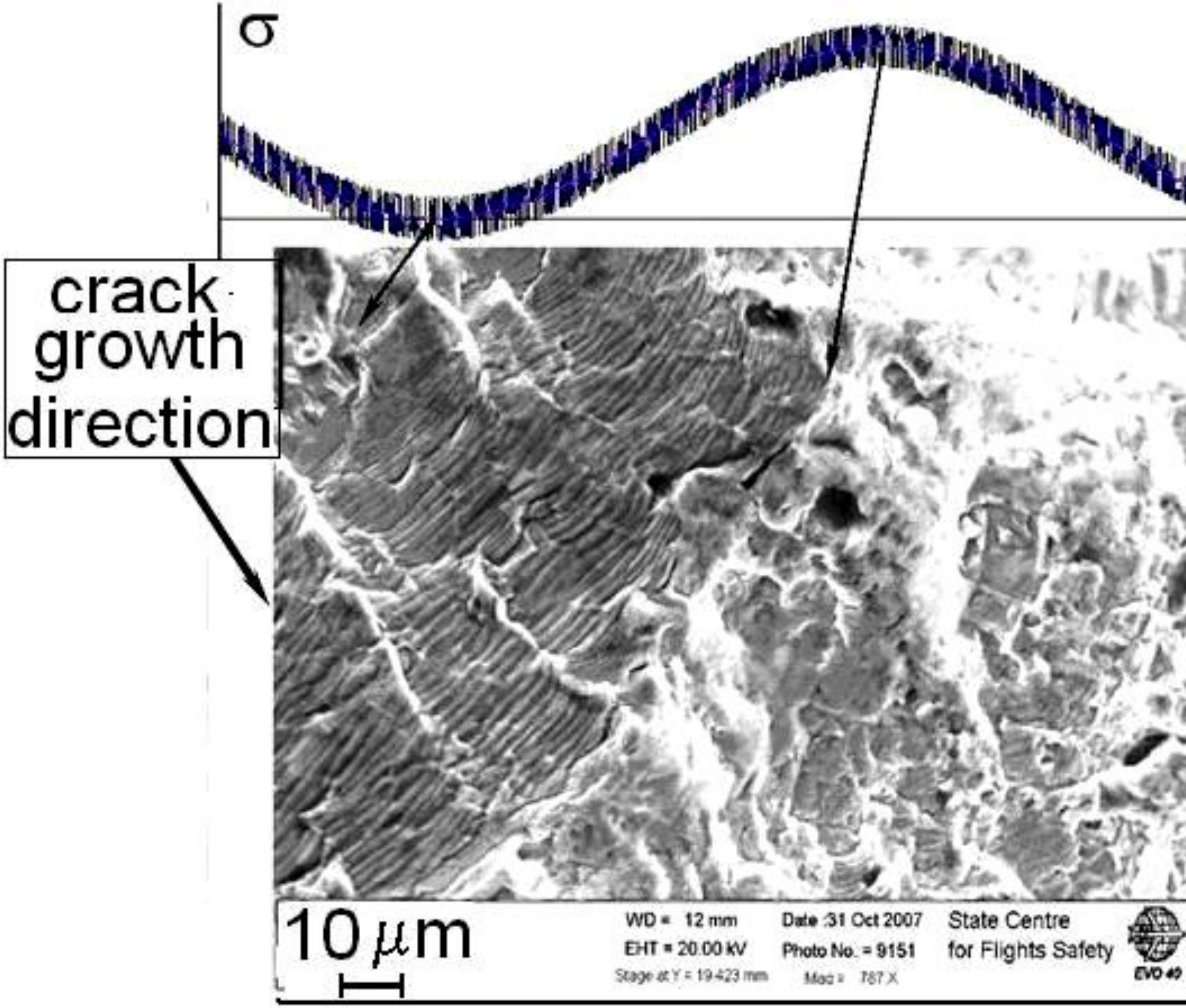
S-N curves for tested specimens under different cyclic loads conditions



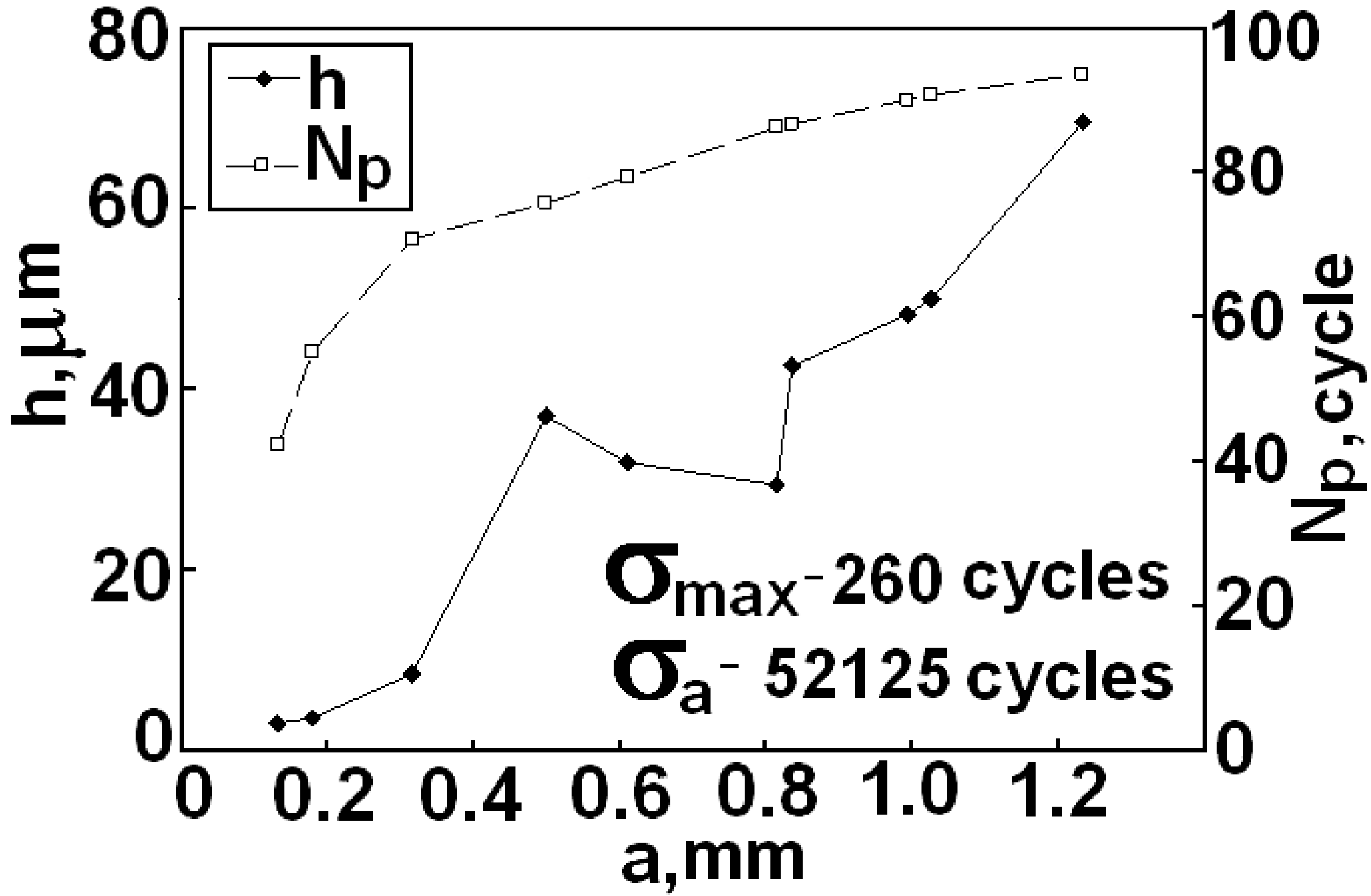
Surface area near the fast fracture



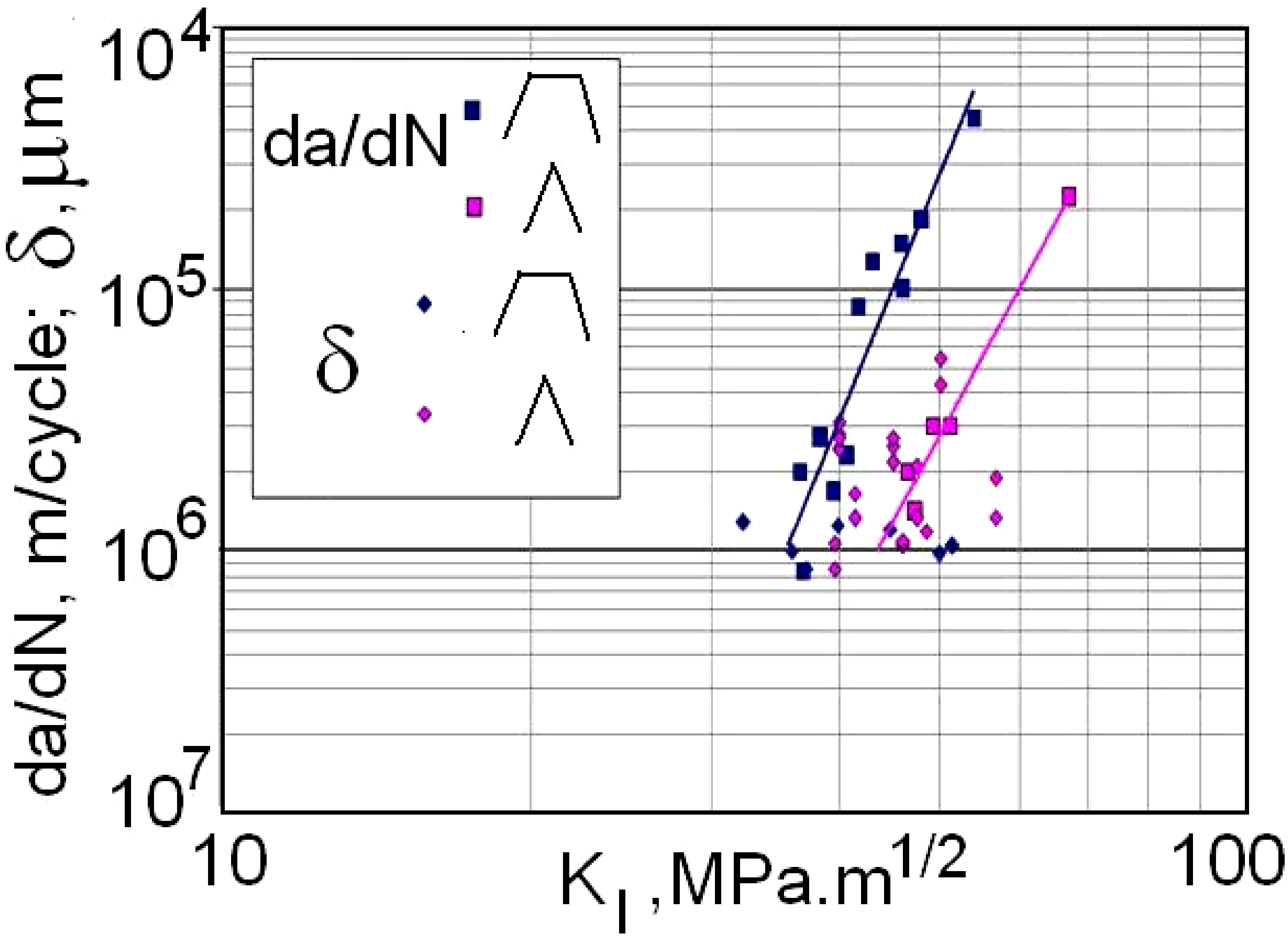
Fracture surface at the transition to the fast fracture



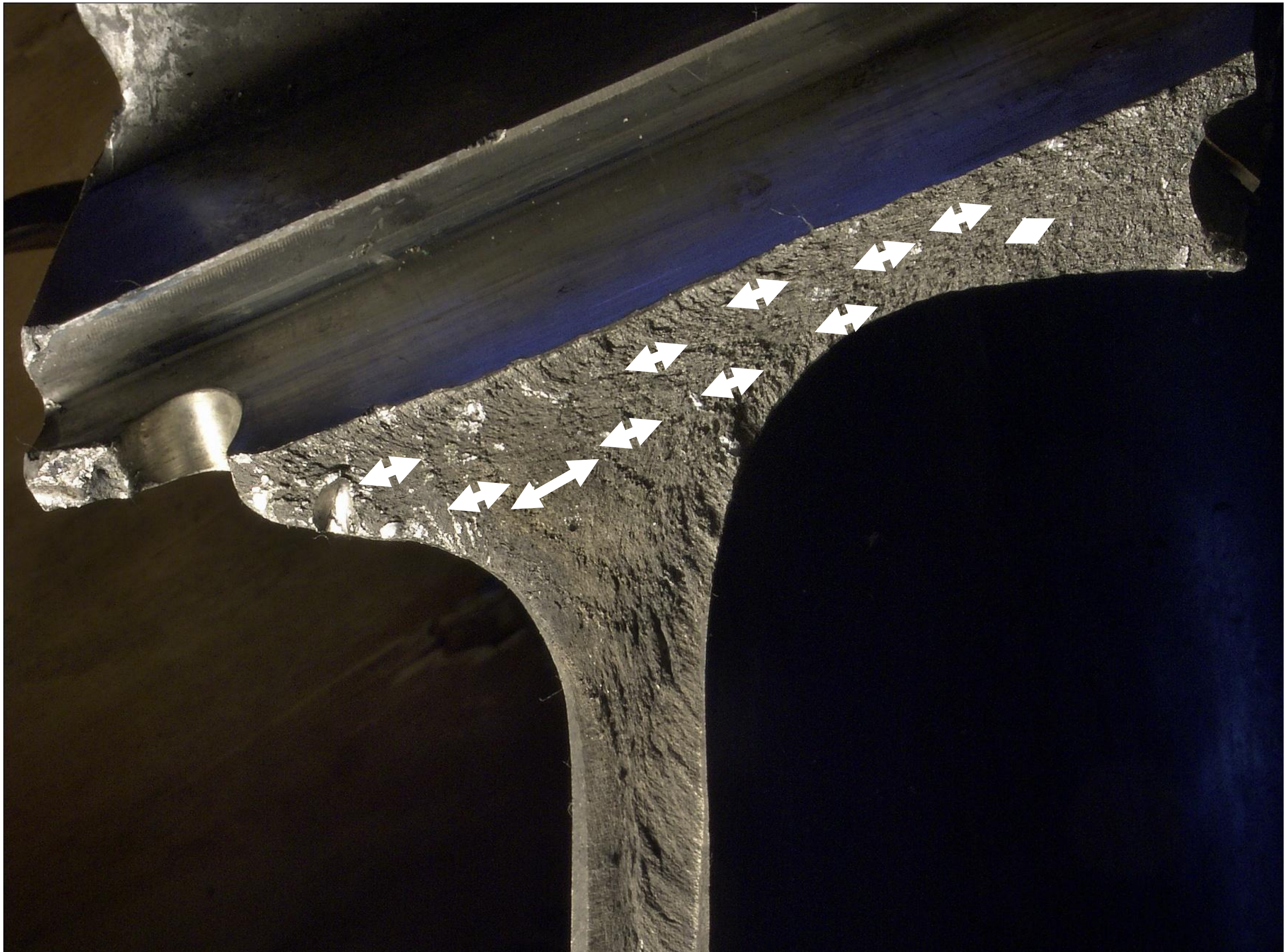
Fatigue crack increment during one block of cyclic loads versus crack growth length for the tested specimen under stresses σ_a = 210 MPa and $\sigma_{мax}$= 500 MPa.



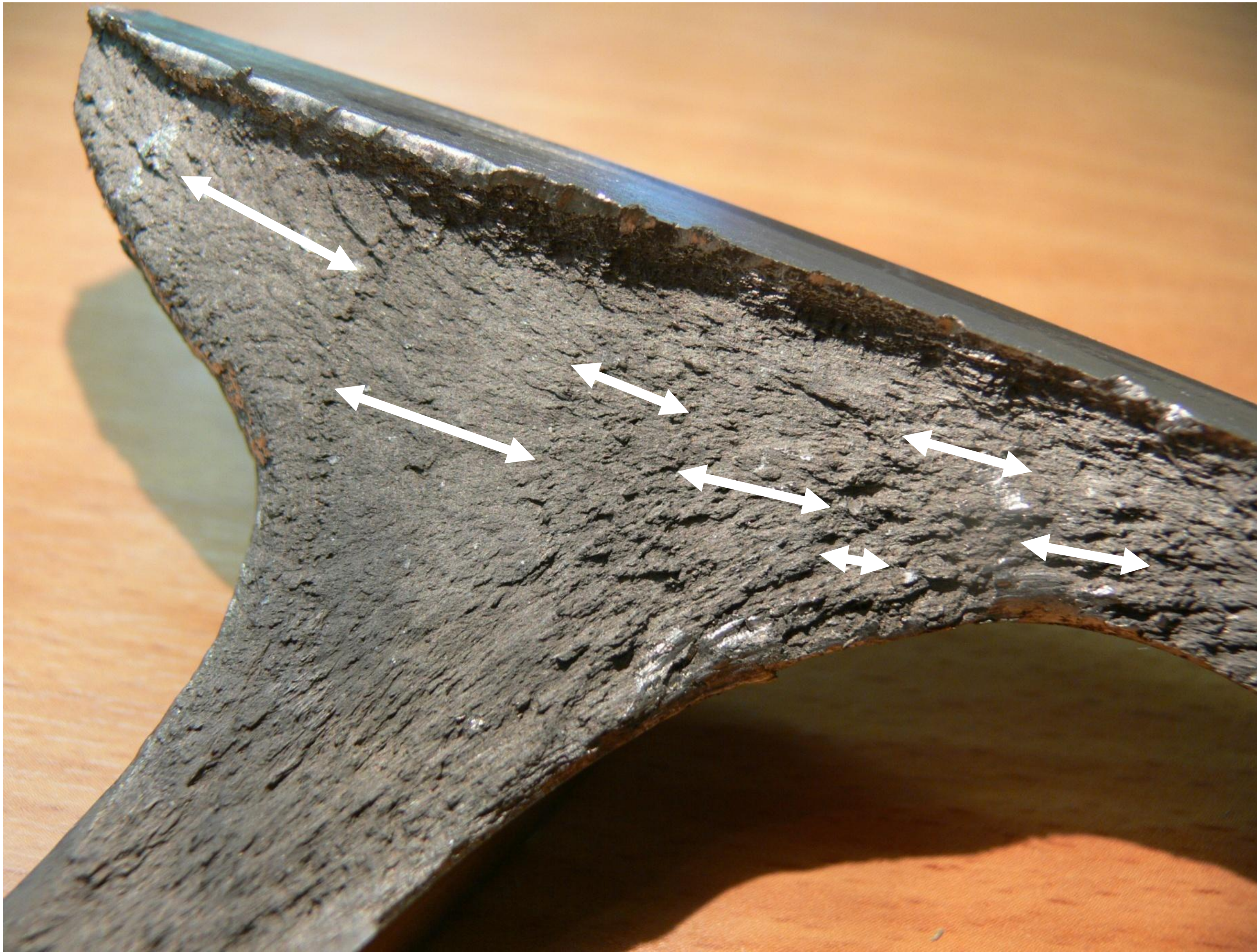
RESULTS OF SPECIMENS FATIGUE TEST AND FRACTOGRAPHIC ANALYSES FOR THE TITANIUM DISK No2 (6100 FLIGHTS TO FAILURE)



BLOCKS OF FRACTURE SURFACE REFLECTING FOR DISK No2 NOT MORE THAN 25 FLIGHTS



BLOCKS OF FRACTURE SURFACE REFLECTING FOR DISK No3 NOT MORE THAN 15 FLIGHTS

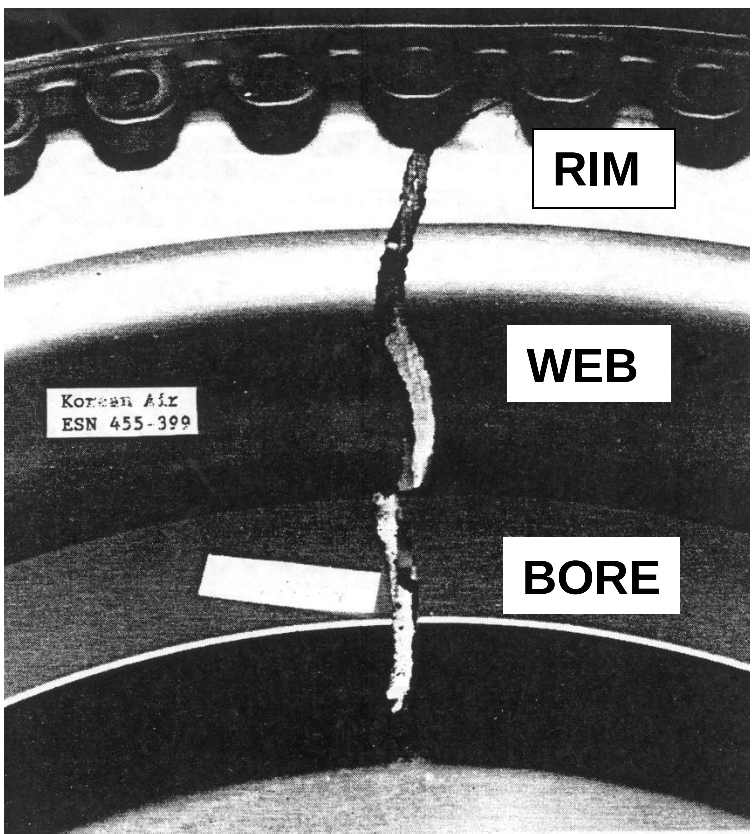


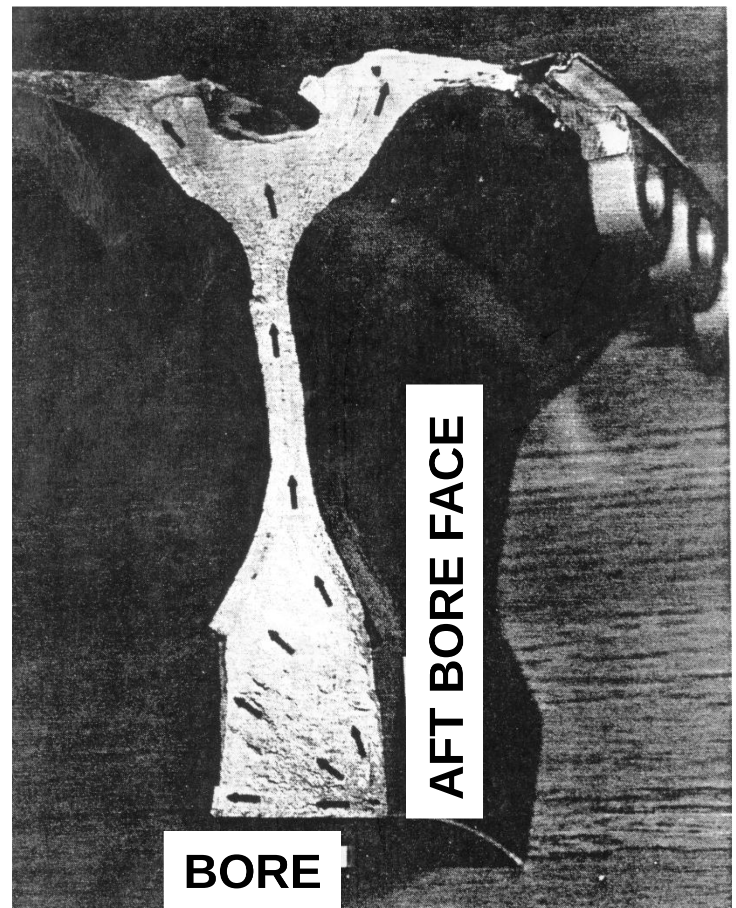
CONCLUSION

TITANIUM DISK FATIGUE CRACKING OCCURS NOT MORE THAN DURING <u>**15 FLIGHTS**</u> BECAUSE OF <u>***LCP+HCF***</u> REGIME

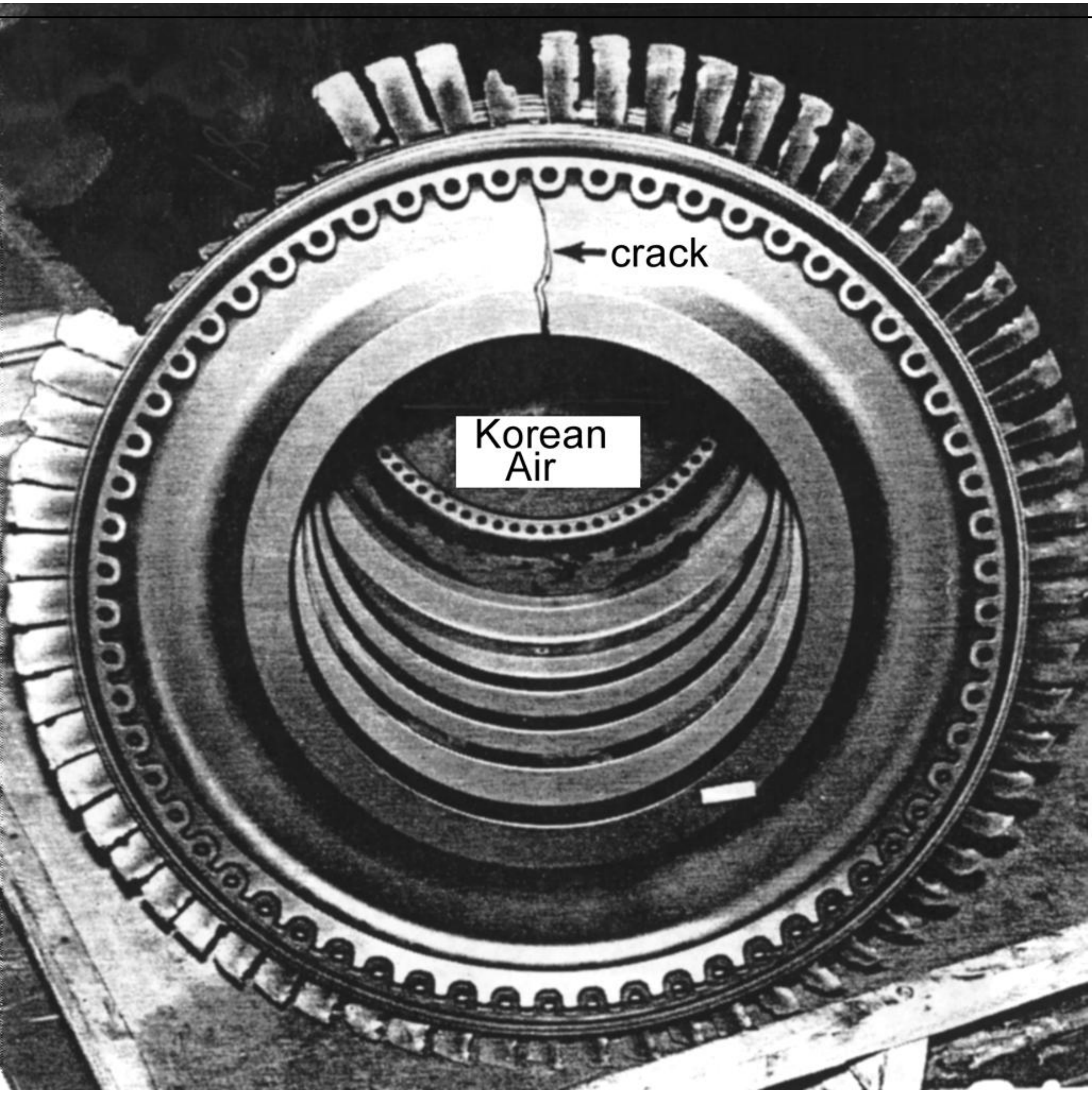
AIRCRAFT ENGINE GF6-50 OF GENERAL ELECTRIC TITANIUM SPOOL OF 3-9 HPC

PHOTOGRAPH (a) DOCUMENTING THE AS-RECEIVED CONDITION OF **<u>GF6-50 3-9 HPC SPOOL</u>** That SUSTAINED a RADIAL BORE TO RIM SEPARATION IN THE STAGE NINE DISK. THE SPOOL WAS MANUFAC-TURED FROM 16" BILLET MATERIAL. CRACK INITIATION (b) OCCURRED FROM THE AFT-BORE CORNER REGION IN the STAGE NINE DISK AND PROPAGATED TOWARDS THE FORWARD SIDE OF THE DISK, UP THE WEB AND INTO THE RIM/SLOT BOTTOM. The AFT-BORE CORNER ORIGIN REGION EXHIBITED A GOLD OXIDATION TINT AND A VISUALLY EVIDENT REGION OF QUASI-CLEAVAGE FRACTURE.





CRACK IN THE “KOREAN” TITANIUM DISK BORE OF THE 9-TH STAGE OF THE HPC SPOOL AND OPENED FRACTURE SURFACE. CRACK GROWTH – **1000** FLIHGTS.



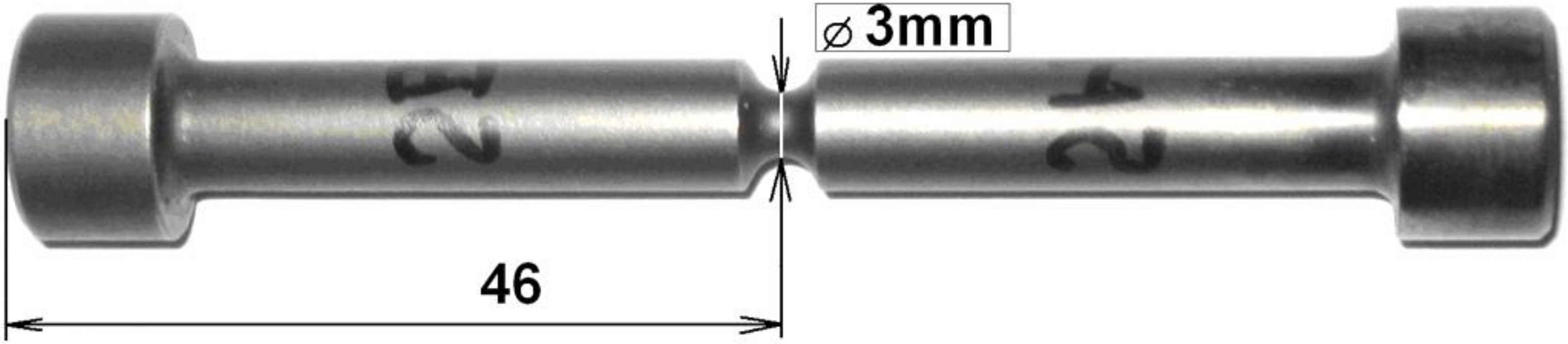
HCF-VHCF

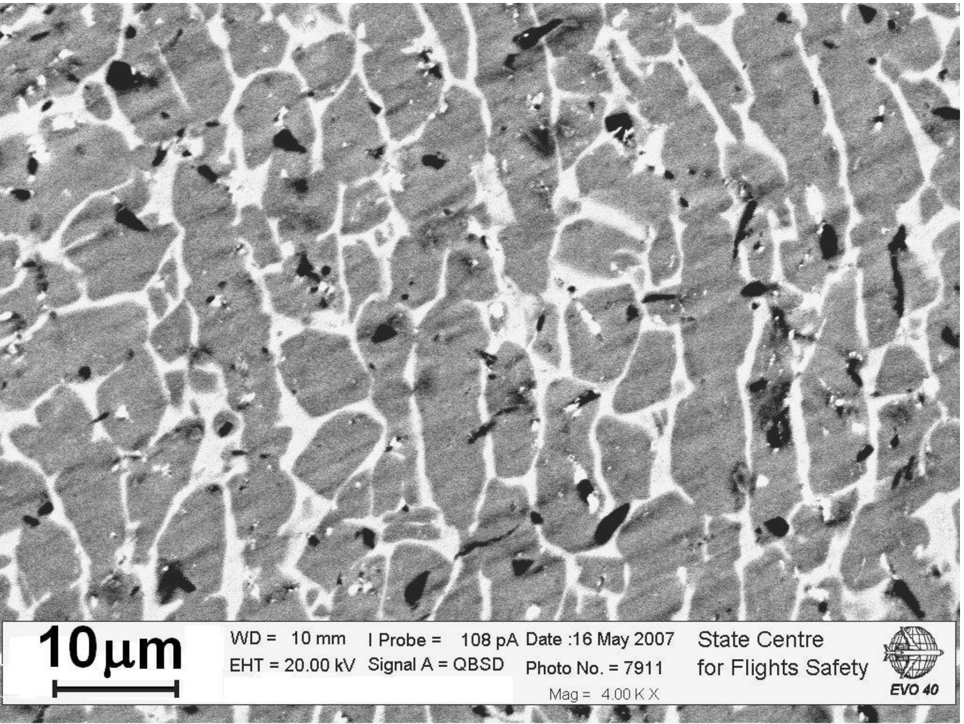
Mechanical properties and material composition of the investigated titanium alloy VT3-1

Ultimate tensile stress - 1200-1400 MPa;
Yield stress – 1000-1200 MPa.
Elongation – 20-30%

Material composition (wt%)									
Ti	Al	Mo	Zr	Si	C	Fe	O_2	N_2	H_2
Remain-der	5.8-7.0	2.8-3.8	0.8-2.5	0.2-0.35	$\leq$0.1	$\leq$0.25	$\leq$0.15	$\leq$0.05	$\leq$0.015

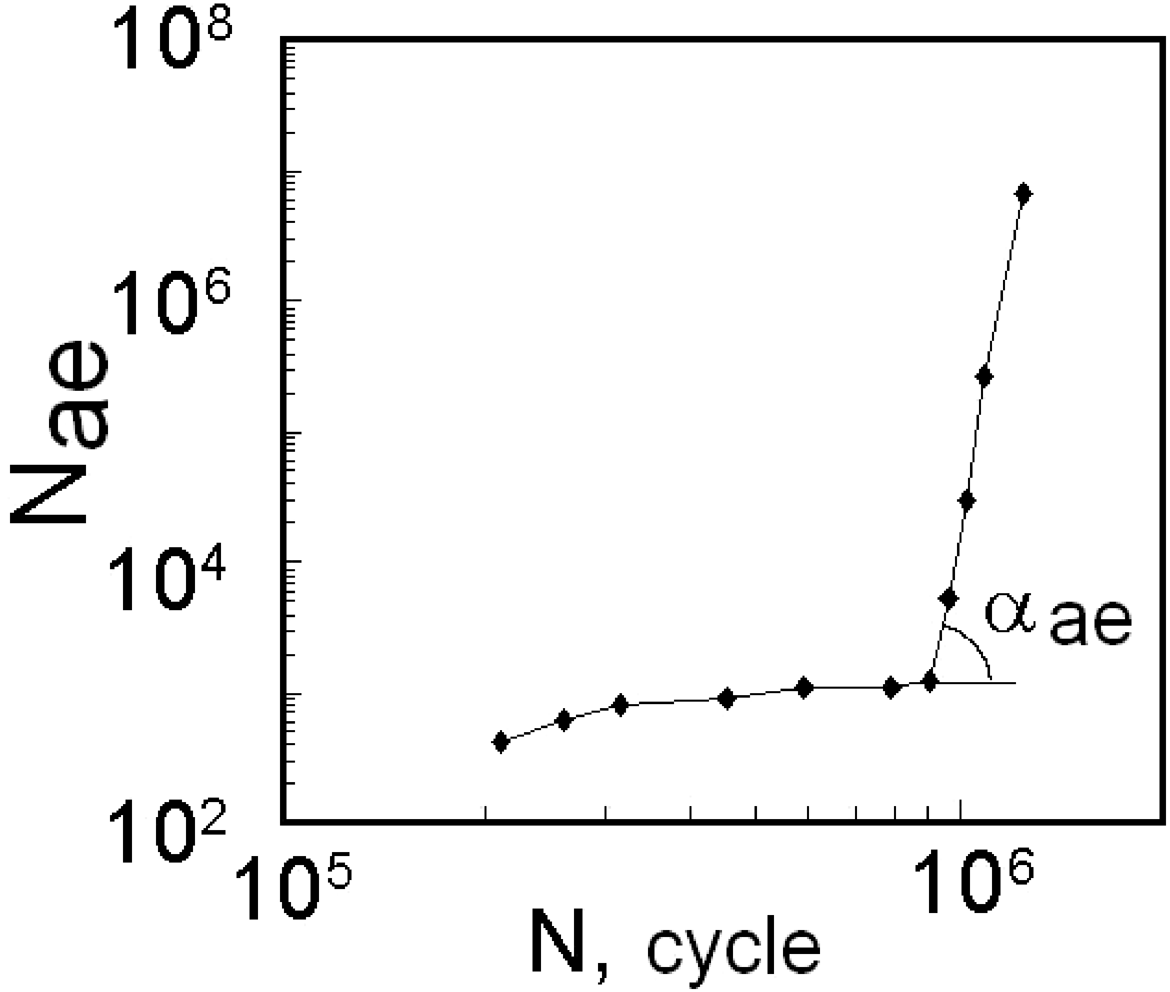
Shape of notched specimens used in fatigue tests of titanium alloy VT3-1



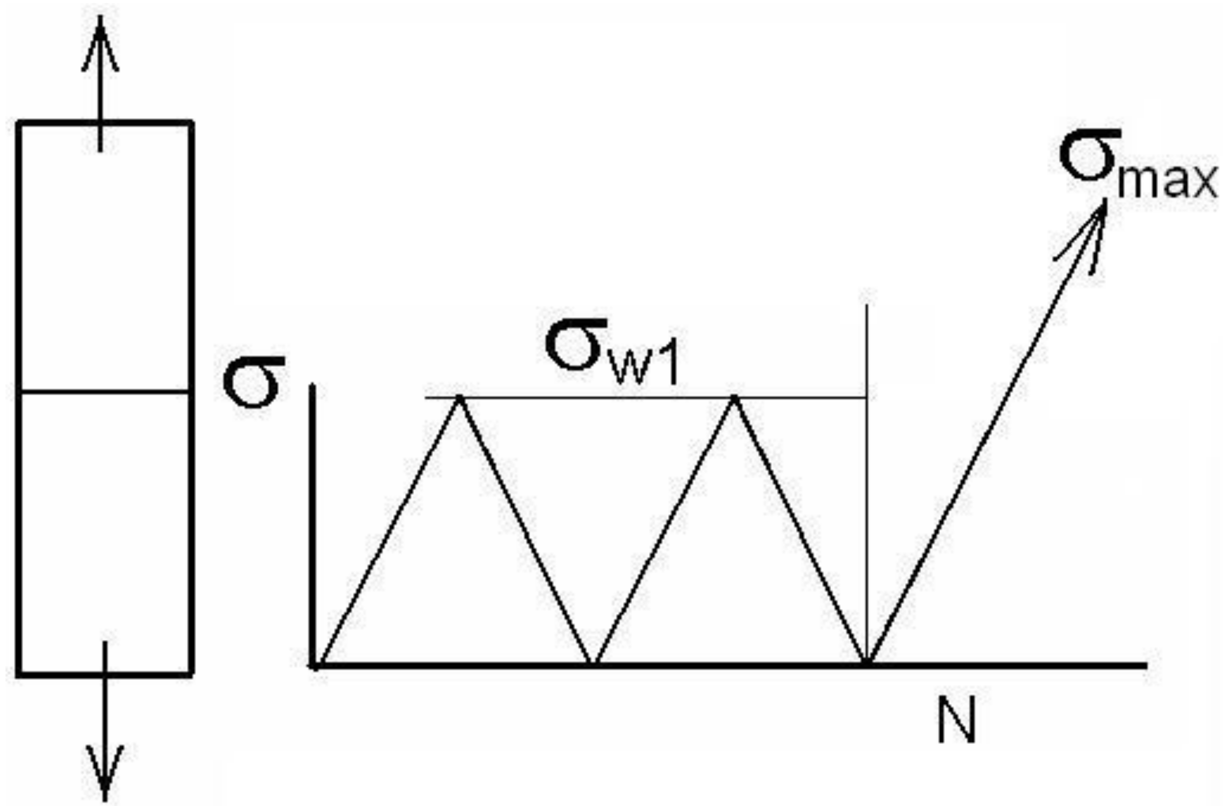


Specimens had the slightly hardened surface in the depth approx. 0.2mm

DEPENDENCE OF Acoustic Emission (AE) SIGNALS ON NUMBER OF CYCLES FOR ONE OF THE FATIGUED BLADES WITH CRACK ORIGINATION REGISTRATION AT THE SURFACE BY THE α–CRITERION



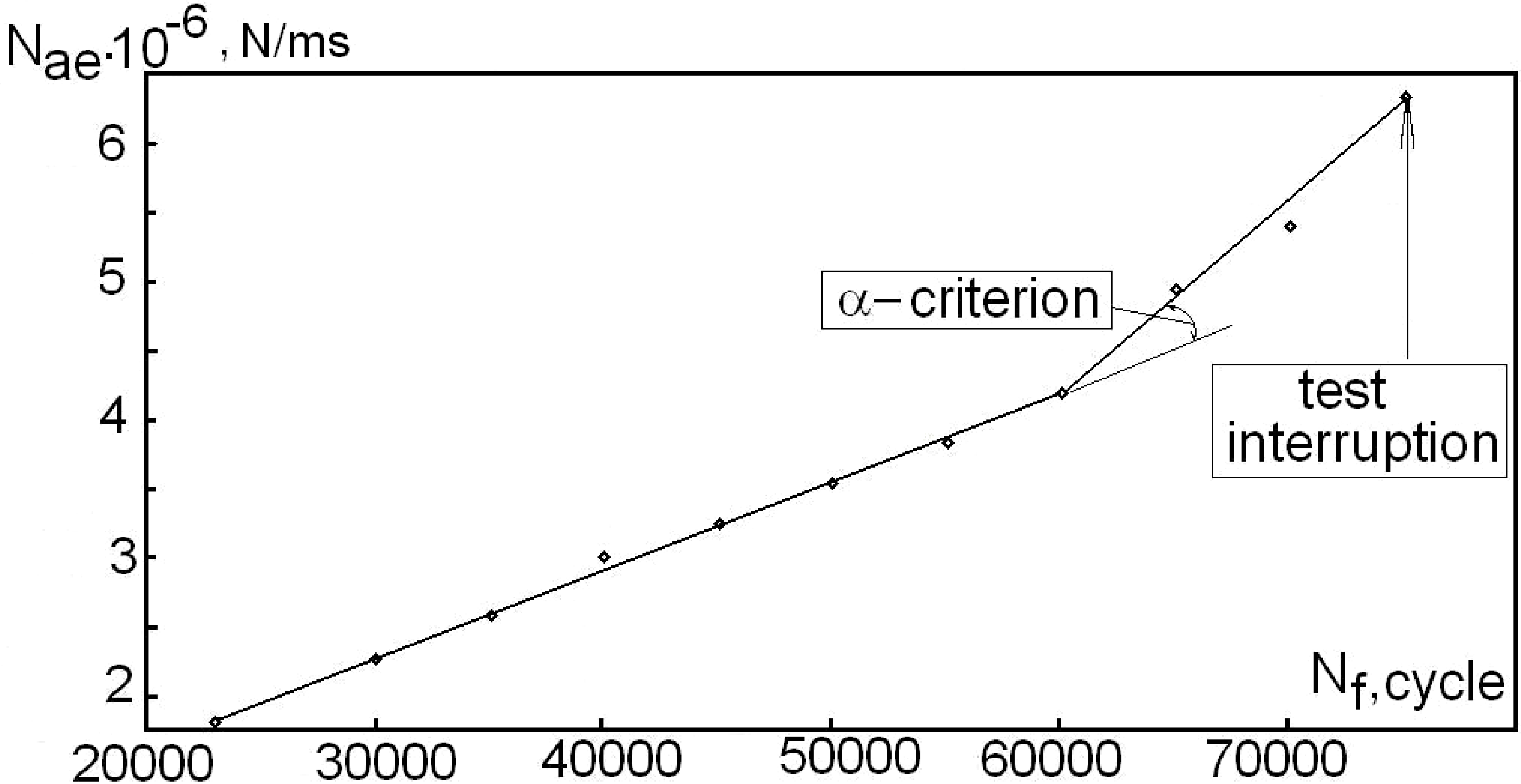
Schema of specimens monotonic tests after the fatigue tests without cracks performed by the specimen surface

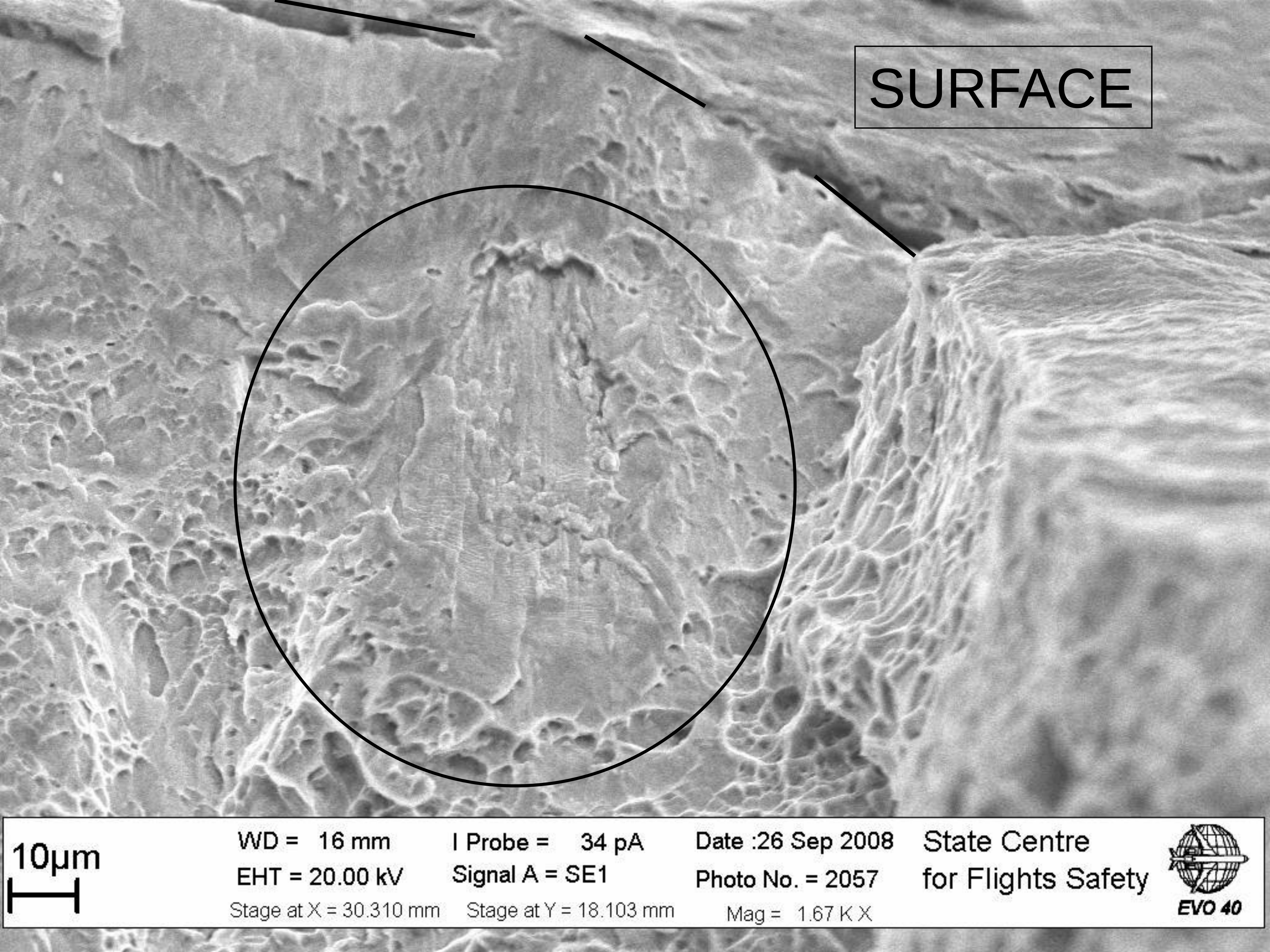


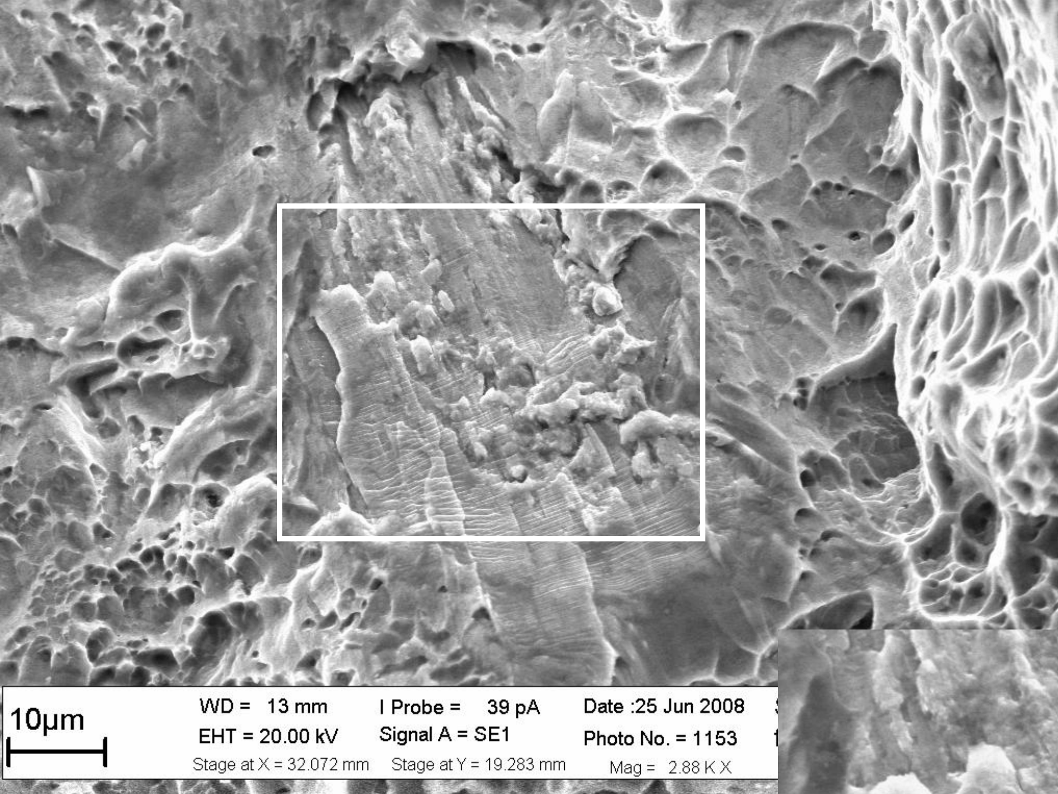
TESTS DATA FOR FATIGUE FREQUENCY of 30Hz

n	Number of cycles	Maximum stress, MPa	Stress ratio	Tension speed, mm/c	Stress at static fracture, kN
1	75084	720	0.31	0.005	18.6
2	415104	700	0.36	0.01	18.2
3	4725809	680	0.38	0.005	18.0

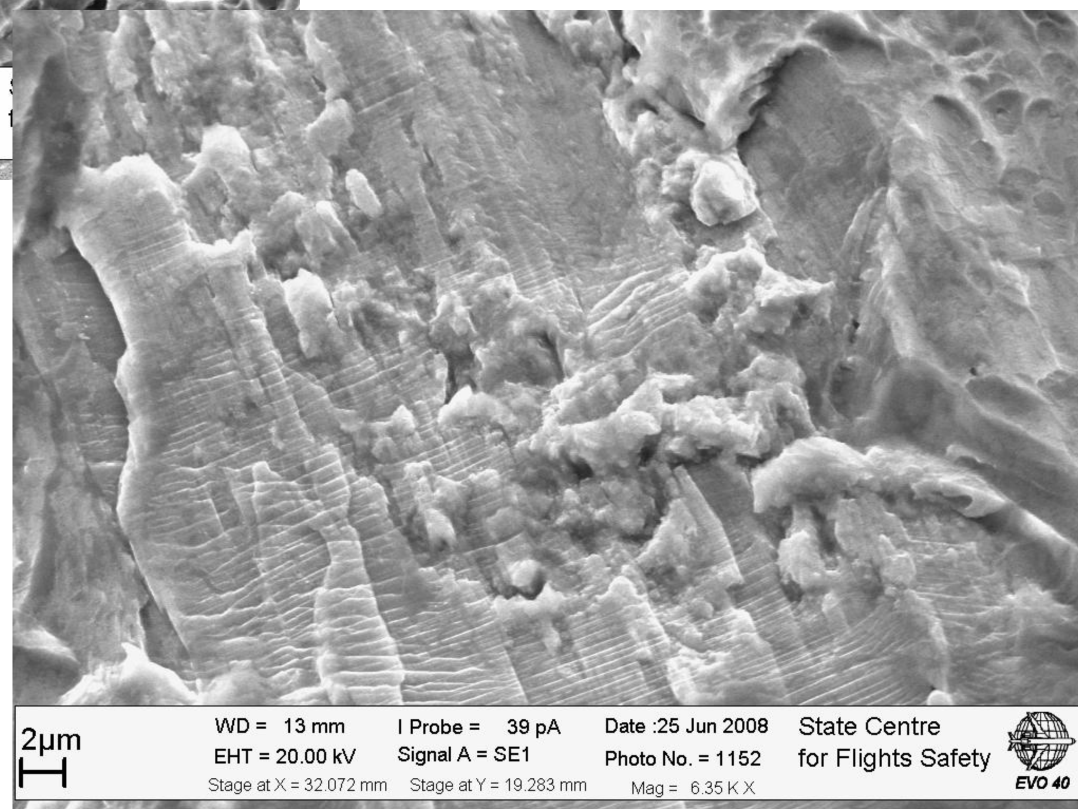
AE-SIGNALS VERSUS NUMBER OF CYCLES FOR THE SPECIMEN TESTED UP TO 75084 CYCLES `



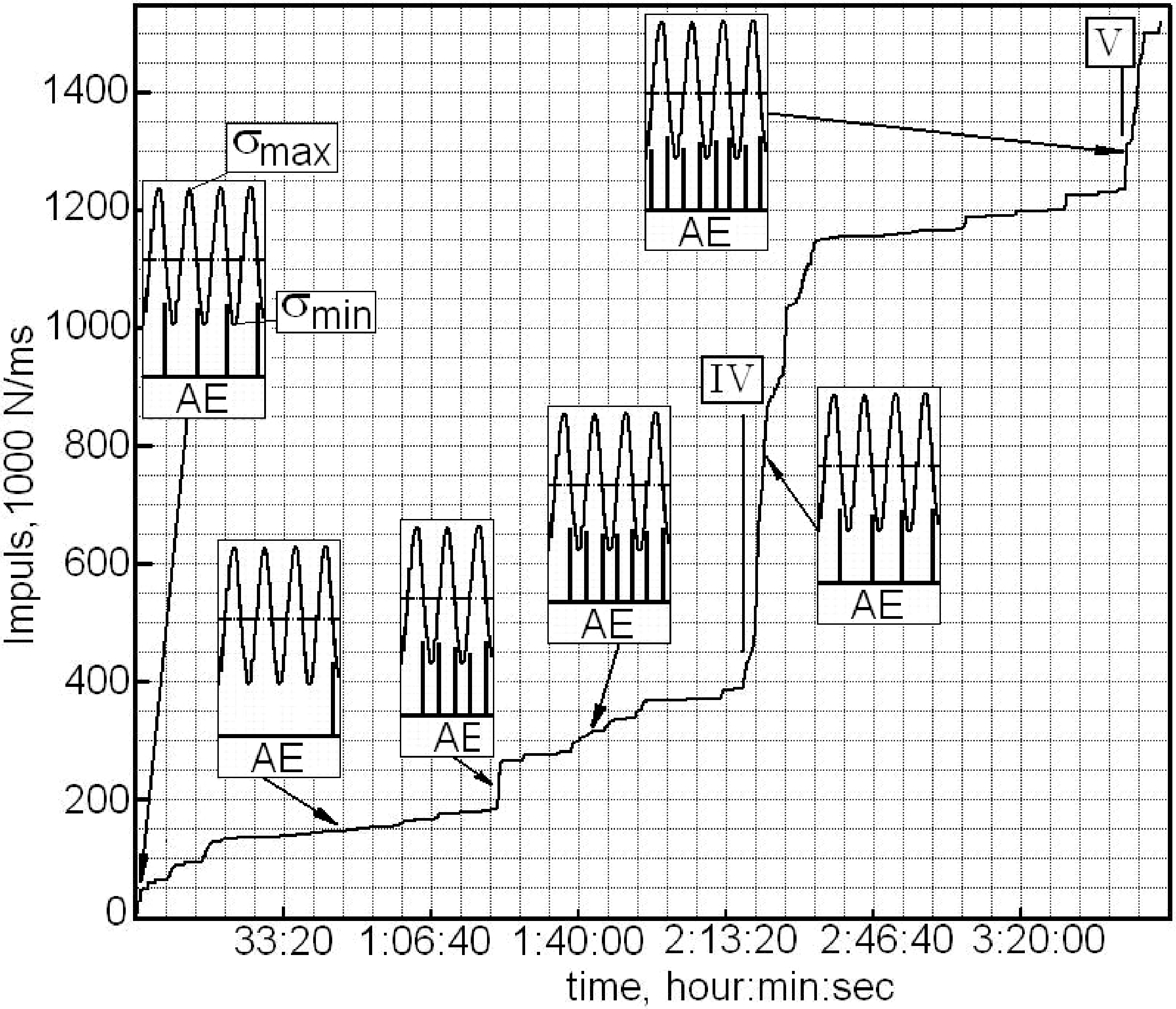

SURFACE
10µm
WD = 16 mm
EHT = 20.00 kV
Stage at X = 30.310 mm
I Probe = 34 pA
Signal A = SE1
Stage at Y = 18.103 mm
Date :26 Sep 2008
Photo No. = 2057
Mag = 1.67 K X
State Centre
for Flights Safety
EVO 40

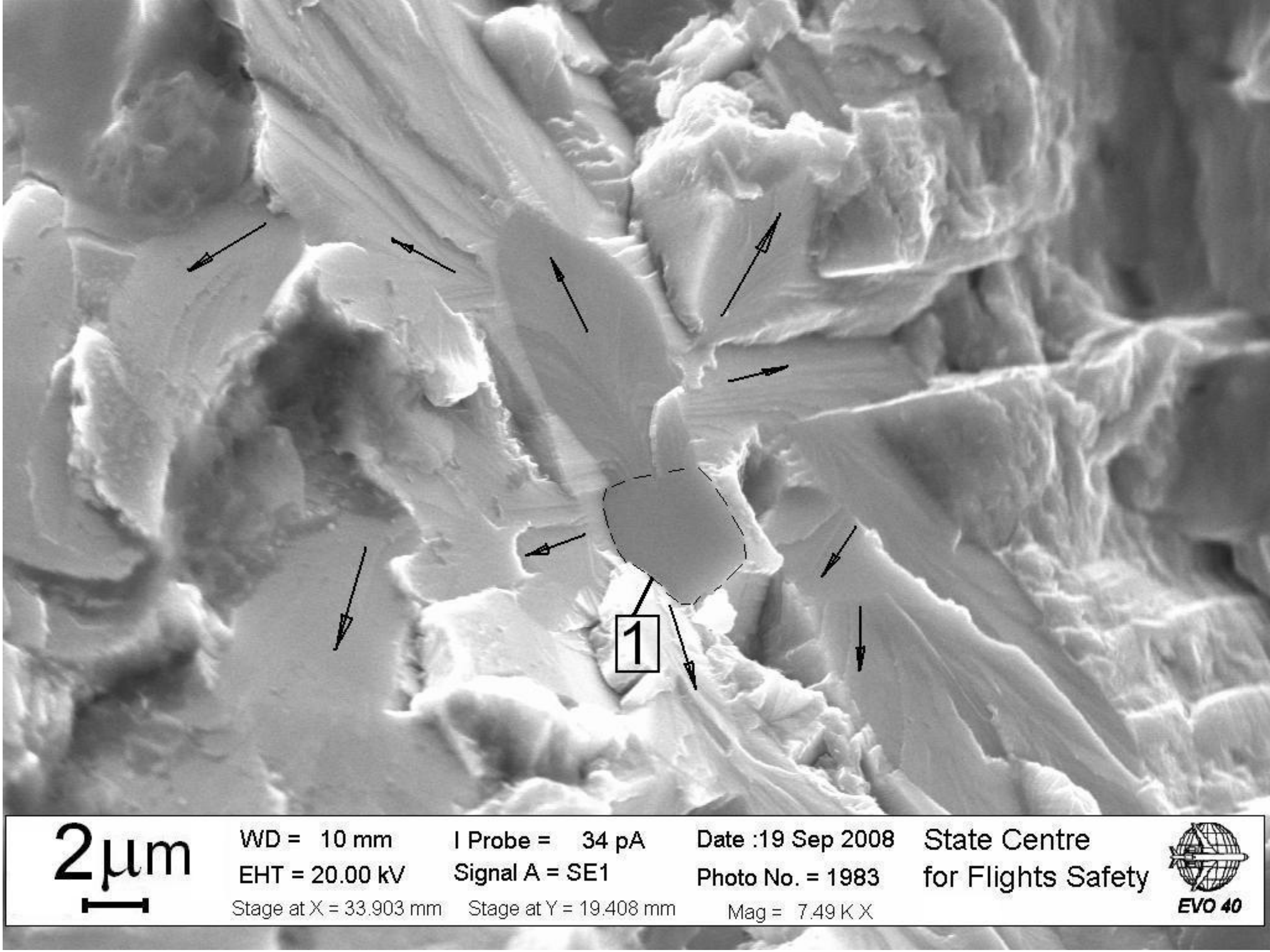

10µm
WD = 13 mm
EHT = 20.00 kV
Stage at X = 32.072 mm
I Probe = 39 pA
Signal A = SE1
Stage at Y = 19.283 mm
Date :25 Jun 2008
Photo No. = 1153
Mag = 2.88 K X

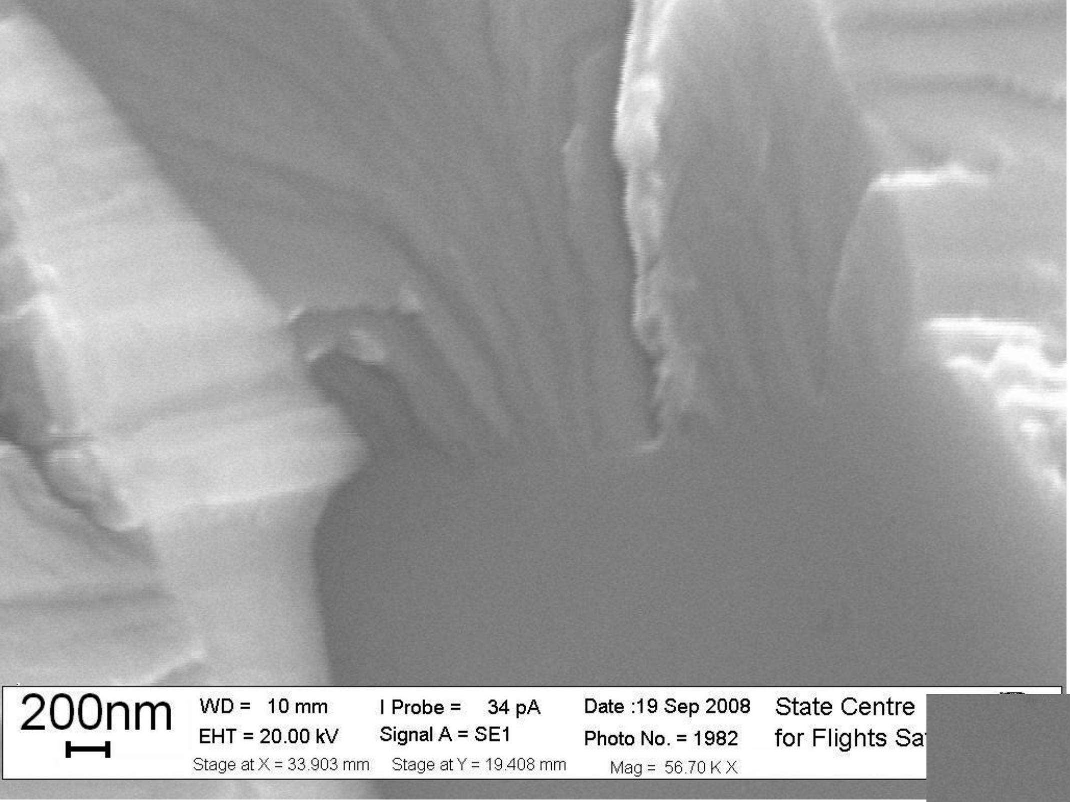
3.4 nm/cycle


2µm
WD = 13 mm
EHT = 20.00 kV
Stage at X = 32.072 mm
I Probe = 39 pA
Signal A = SE1
Stage at Y = 19.283 mm
Date :25 Jun 2008
Photo No. = 1152
Mag = 6.35 K X
State Centre
for Flights Safety
EVO 40

AE-SIGNALS VERSUS NUMBER OF CYCLES FOR THE SPECIMEN TESTED UP TO 415104 CYCLES `

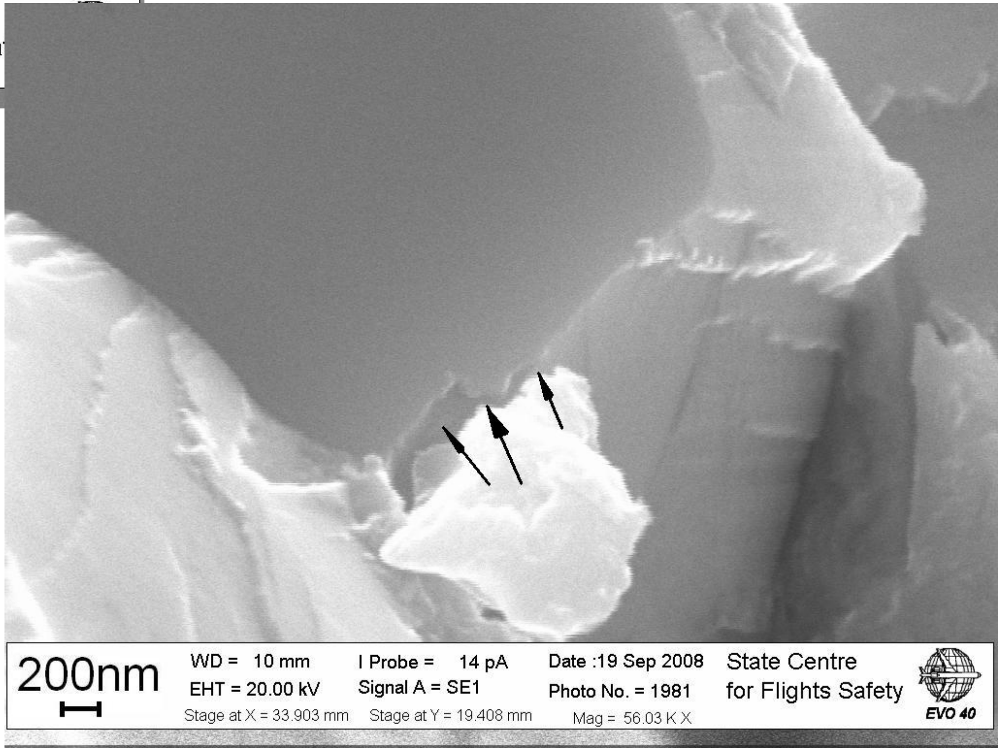



1
2μm
WD = 10 mm
EHT = 20.00 kV
Stage at X = 33.903 mm
I Probe = 34 pA
Signal A = SE1
Stage at Y = 19.408 mm
Date :19 Sep 2008
Photo No. = 1983
Mag = 7.49 K X
State Centre
for Flights Safety
EVO 40



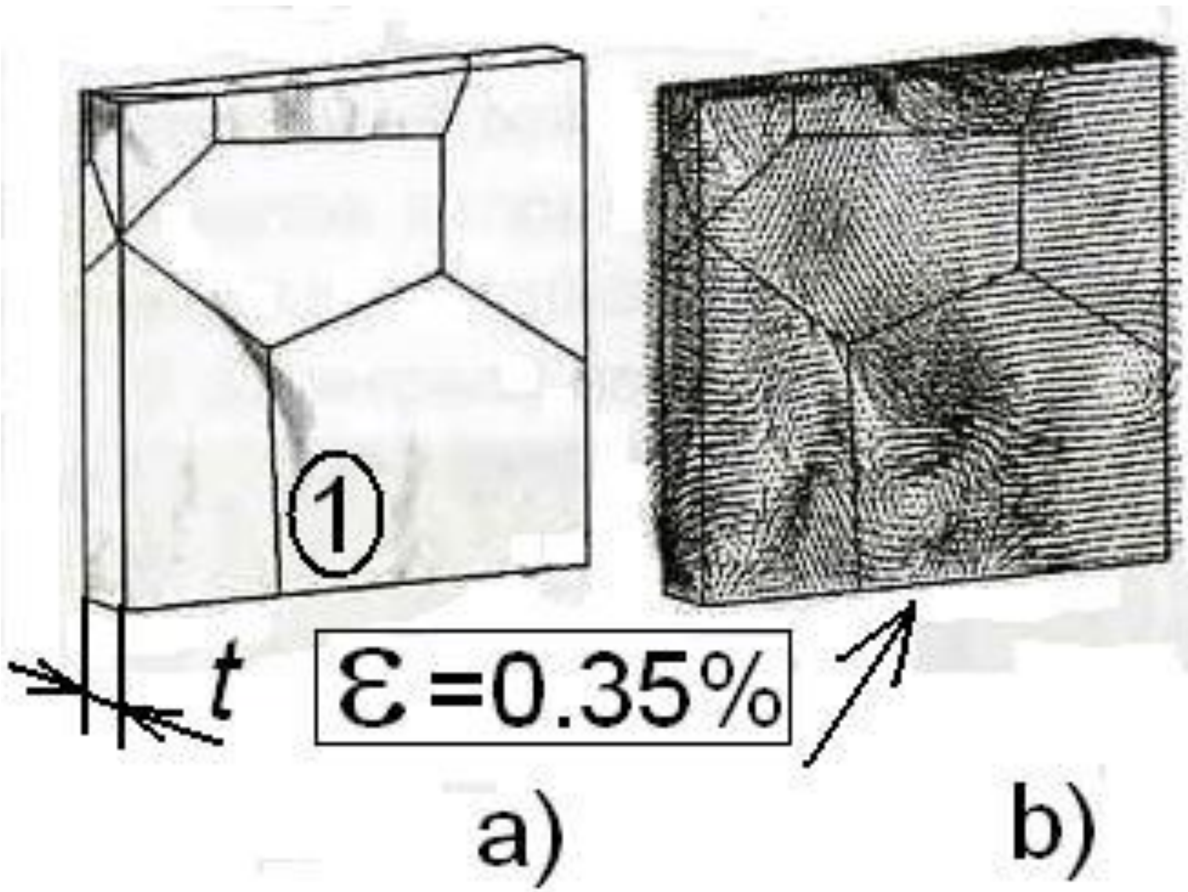
0.8 nm/cycle
1.0 nm/cycle

a=0.3 nm
c = 0.5 nm

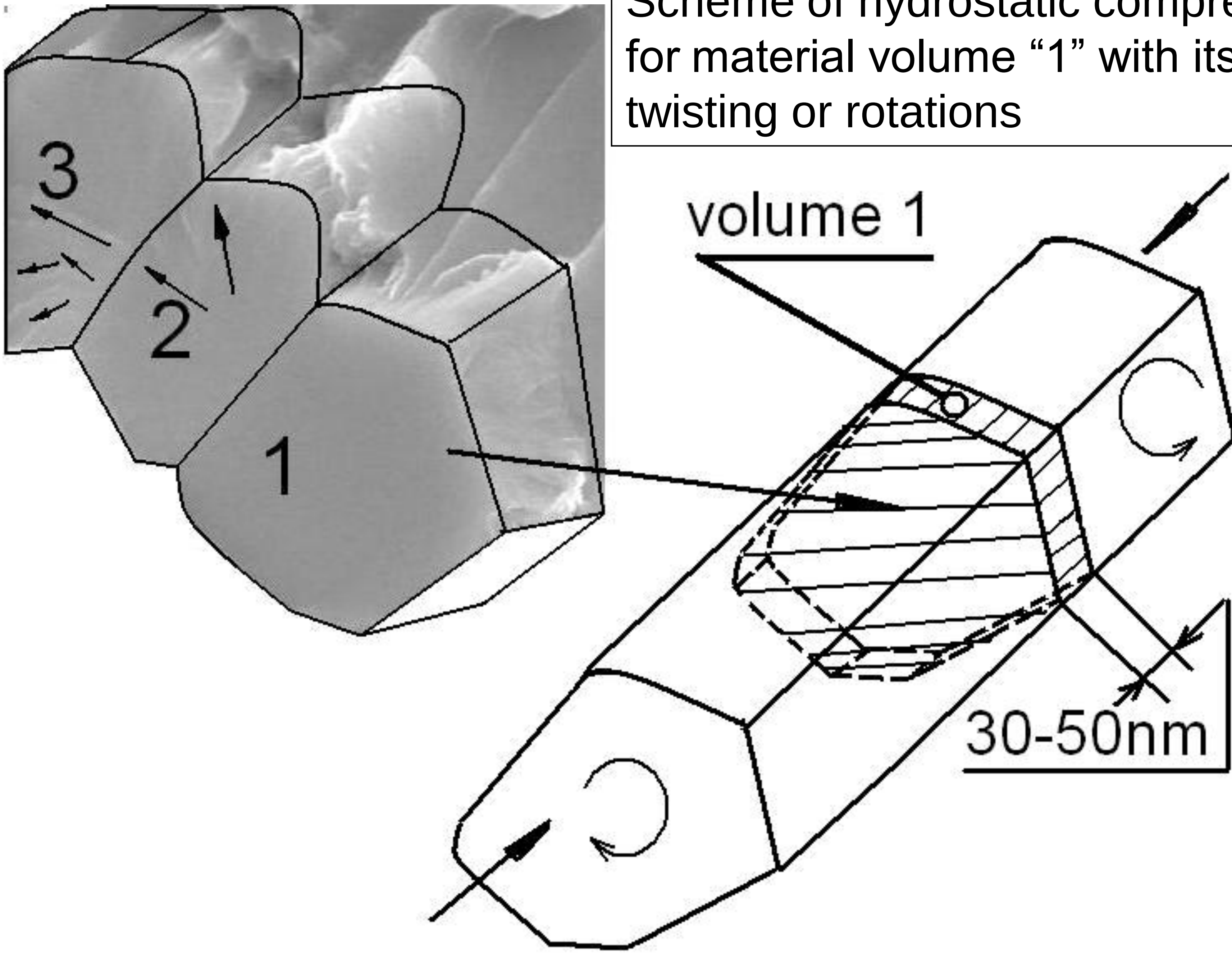


NUMERICAL ESTIMATION of PLASTIC DEFORMATION PROCESSES IN METALS VOLUM INDER TENSION

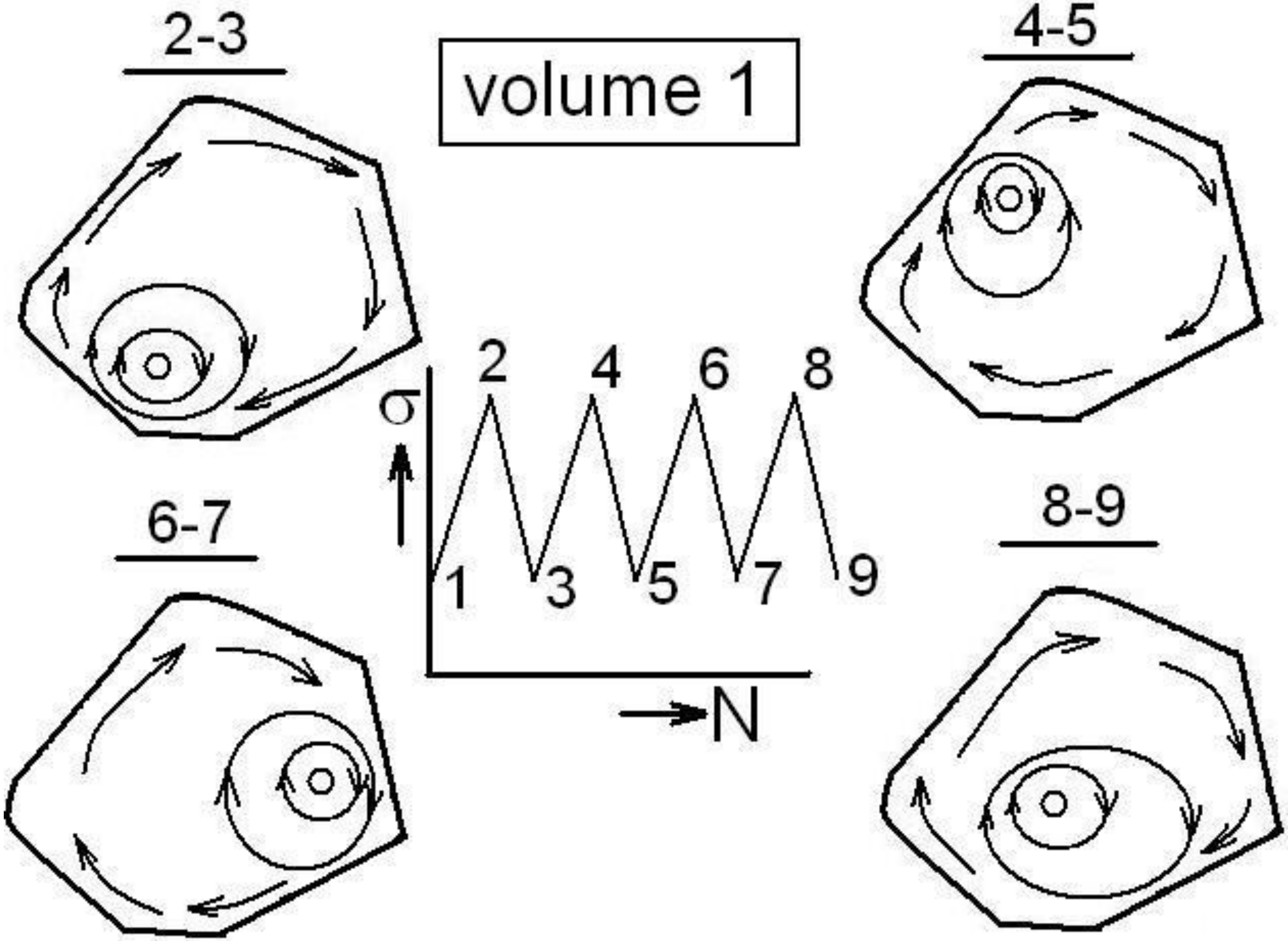
Romanova V.A., Balochonov R.R. (2008)



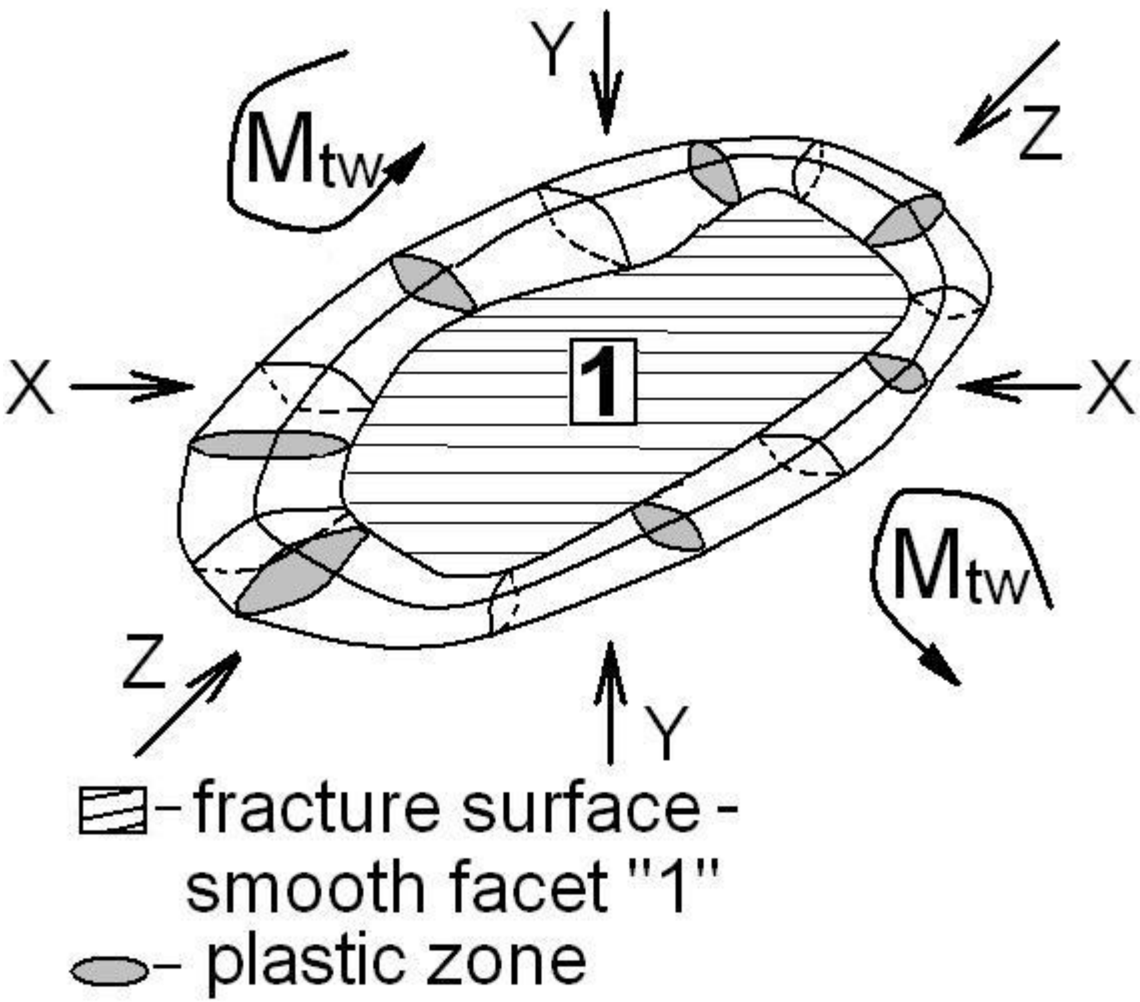
Scheme of hydrostatic compressor for material volume “1” with its twisting or rotations

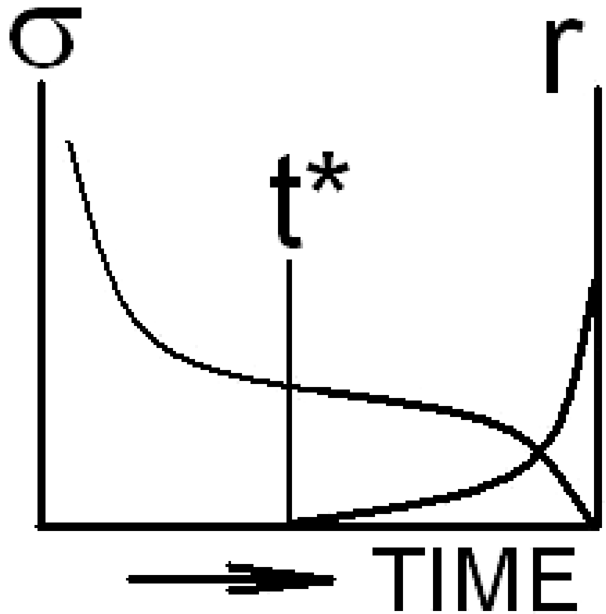


Scheme of material volume “1” destruction under twisting or rotations because of Ultra-High-Plasticity under compression in hydrostatic conditions



FIRST FACET OCCURES BECAUSE OF PLASTIC ZONE FORMATION
OR ONE OF THE CRISTALLOGRAPHIC PLANE DISTRESS?



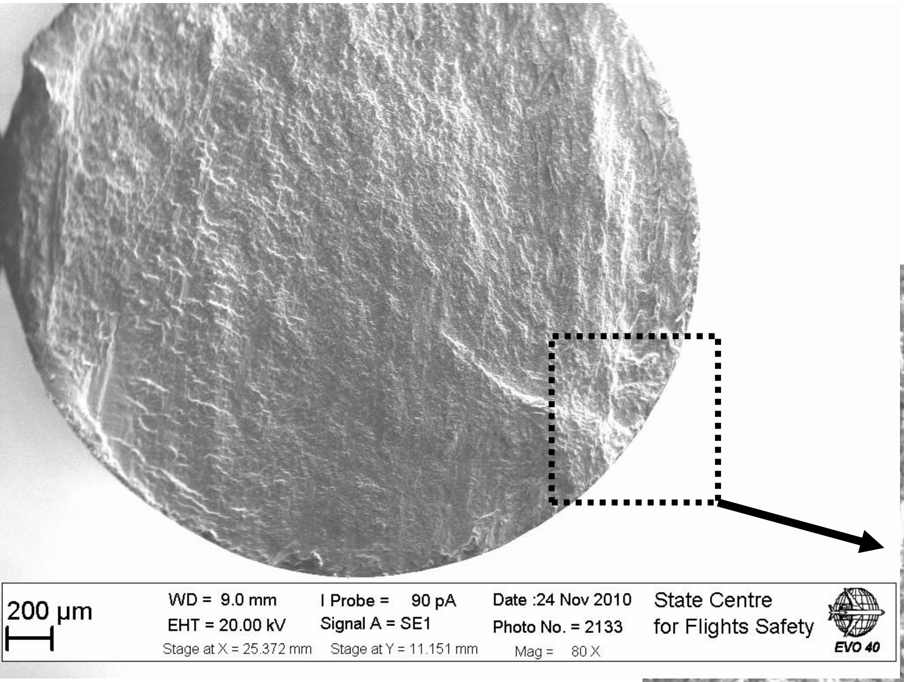


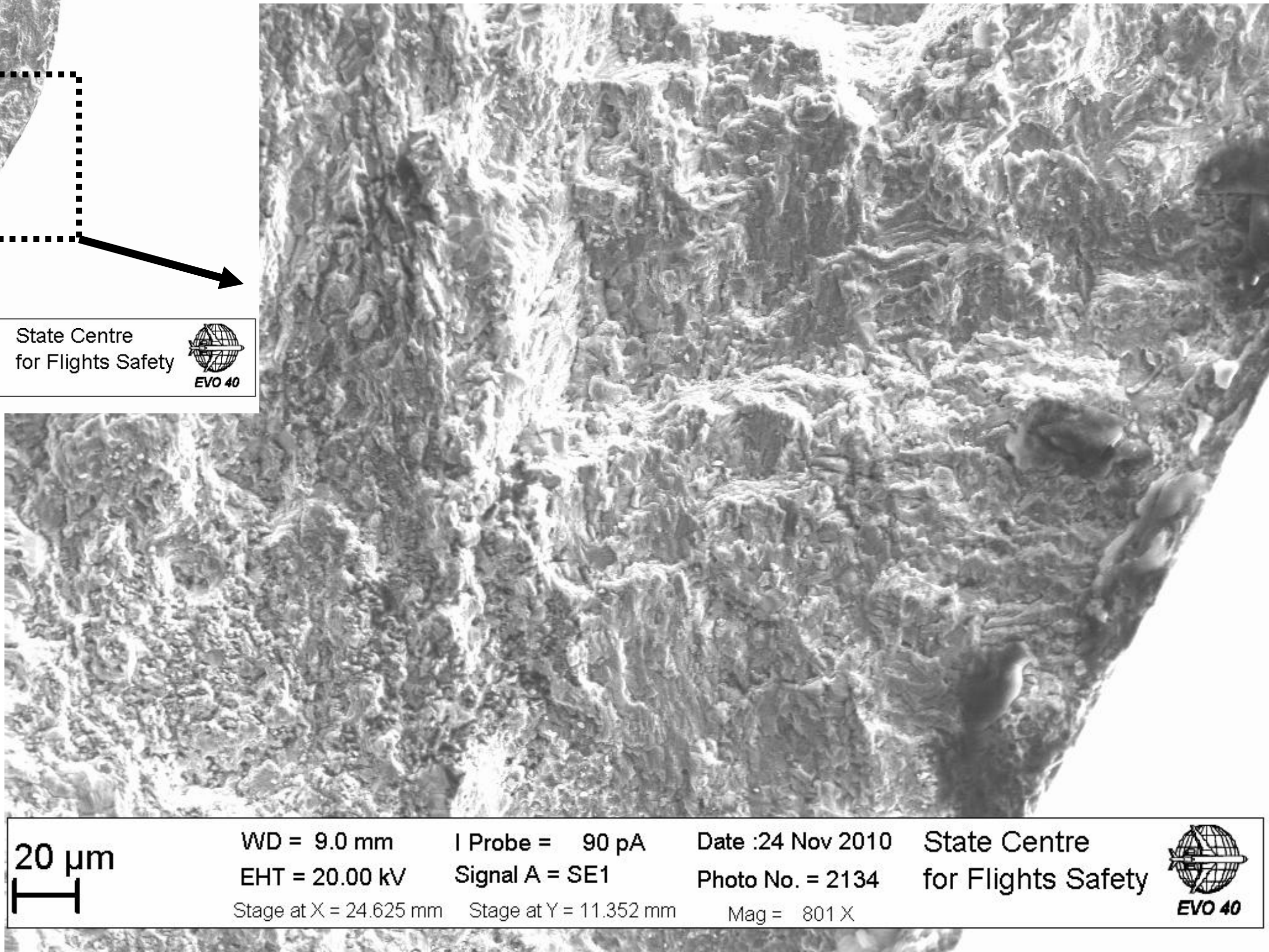
σ – distressing by the "1" facet

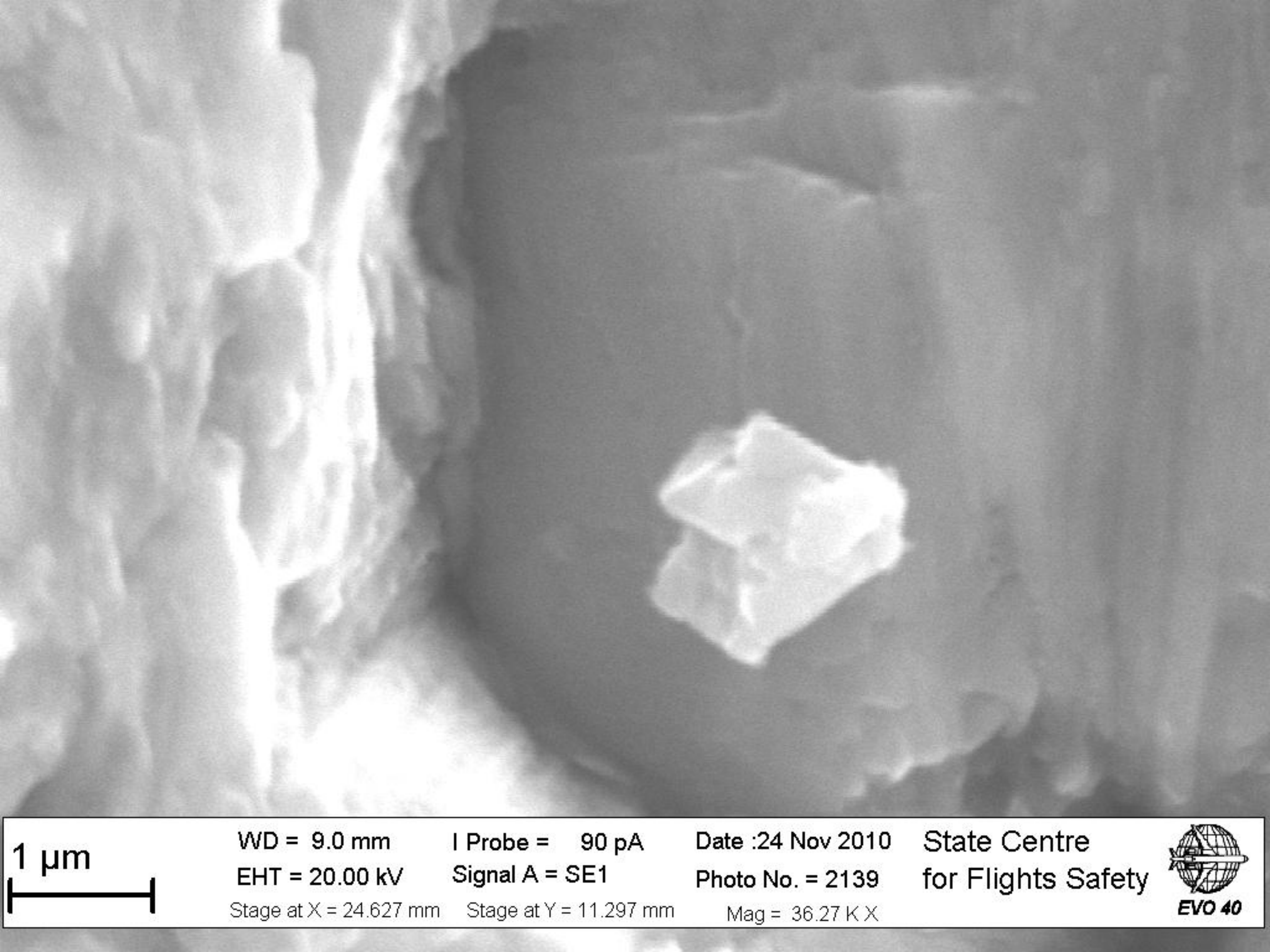
r – plastic zone size

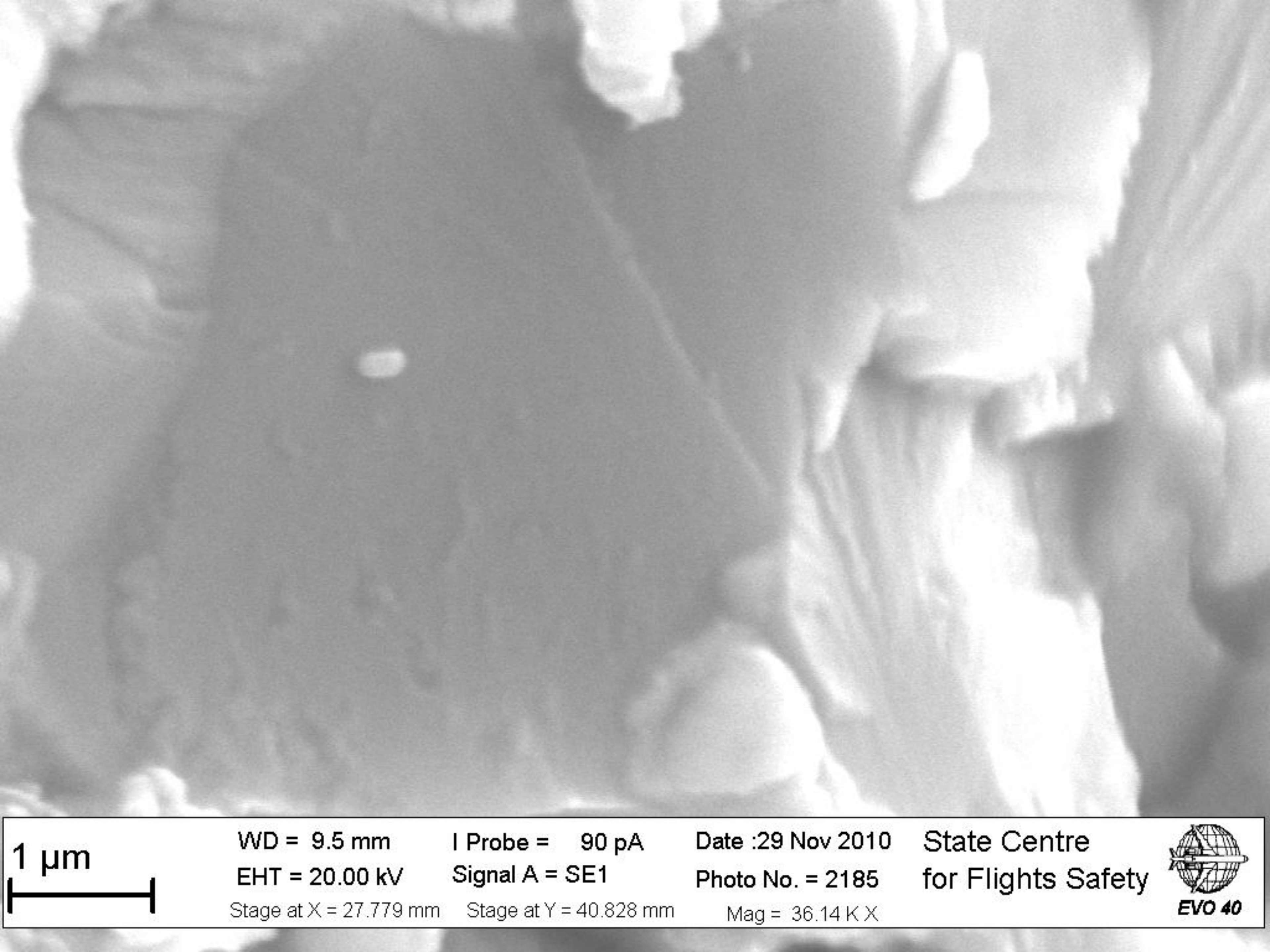
t^* – critical time for **start** of plastic zone formation around the "1" distressed facet

VT3-1. TESTS UNDER 35kHz. Durability $1.2x10^7$ cycles.






1 µm
WD = 9.0 mm
EHT = 20.00 kV
Stage at X = 24.627 mm
I Probe = 90 pA
Signal A = SE1
Stage at Y = 11.297 mm
Date :24 Nov 2010
Photo No. = 2139
Mag = 36.27 K X
State Centre
for Flights Safety
EVO 40


1 µm
WD = 9.5 mm
EHT = 20.00 kV
Stage at X = 27.779 mm
I Probe = 90 pA
Signal A = SE1
Stage at Y = 40.828 mm
Date :29 Nov 2010
Photo No. = 2185
Mag = 36.14 K X
State Centre
for Flights Safety
EVO 40

The material sensitiveness to the dwell-time for titanium alloys is the synergetical problem due to combinations of residual stresses and gases.

The material state for in-service conditions have to be considered in the wide range of this two main parameters combinations.

Criterion for material better state is the value of dwell-time from which quasi-cleavage occurs with facetted pattern fracture surface.

The crack growth acceleration due to the dwell-time influence can be seen in the range of dwell-time 3s – 120s in dependence on the titanium alloy state.

CONCLUDING REMARKS

TITATIUM ALLOYS IN-SERVICE CRACKING DUE TO IN-FLIGHT MULTIAXIAL LOADING IS THE SYNERGETICAL PROBLEM:

(1) IF COMBINATION OF RESIDUAL STRESSES AND INTERNAL CASES INFLUENCED MATERIAL SENSITIVENESS TO DWELL-TIME OR HIGH STRESS RATIO (*R*), FACETTED PATTERN FRACTURE MORPHOLOGY IS DOMINANT AND MATERIAL CRACKING ACCELERATION TAKES PLACE;

(2) THE DISCUSSED COMBINATION INFLUENCED MATERIAL CRACKING IN HCF AND VHCF REGIME UNDER DIFFERENT EXTERNAL COMBINATION OF CYCLIC LOAD PARAMETERS

Mechanical properties and material composition of the investigated titanium alloy **VT3-1**

Ultimate tensile stress - 1000-1200 MPa.
Yield stress – 900-1150 MPa.
Elongation – 20%

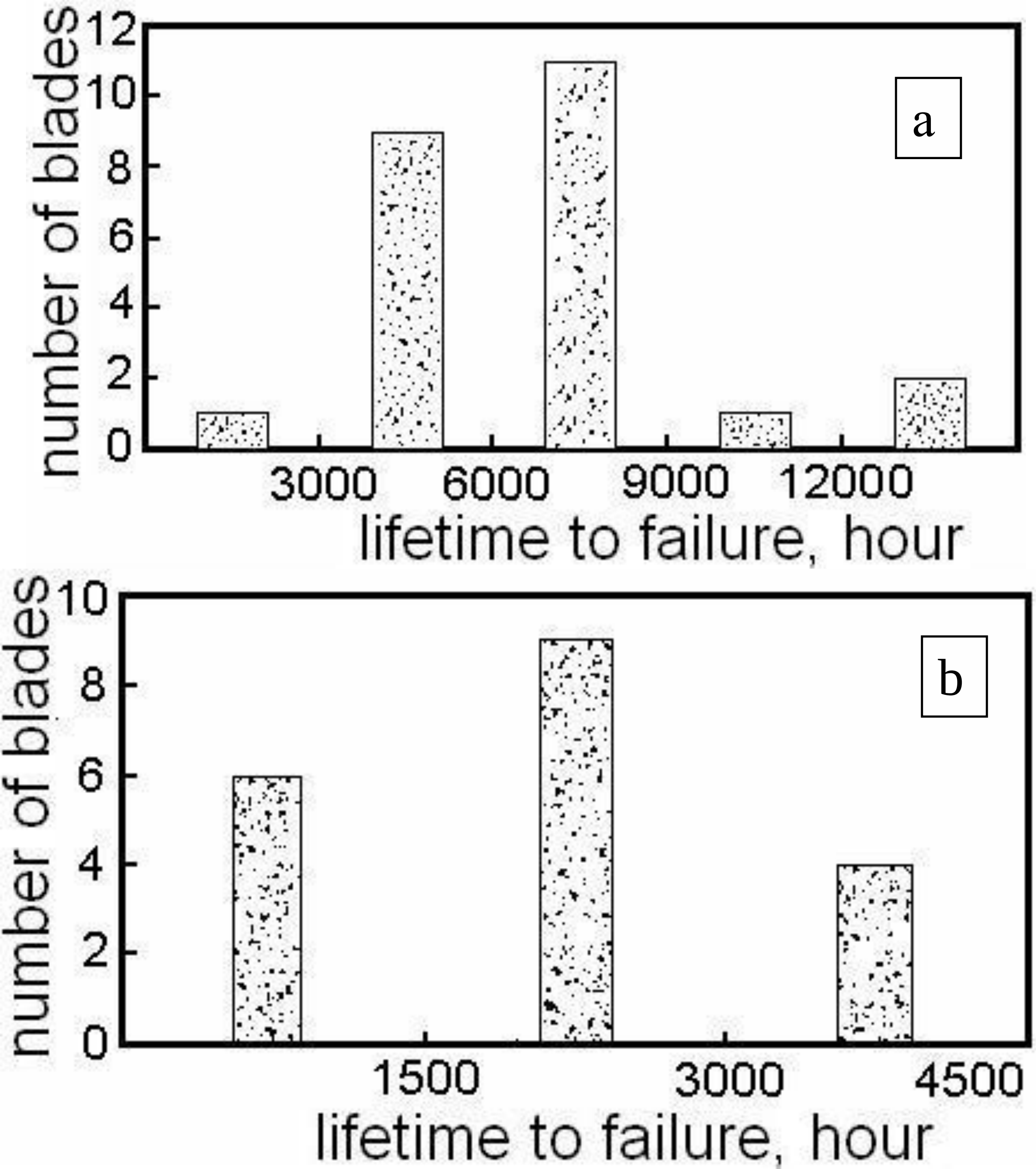
Material composition (wt%)									
Ti	Al	Mo	Cr	Si	Fe	C	O_2	N_2	H_2
Remainder	5.5-7.0	2.0-3.0	0.8-2.3	0.15-0.4	0.2-0.7	≤0.1	≤0.18	≤0.05	≤0.015

Overview of the fracture surface patterns in area of origin of the blade with center of the crack origination placed under the surface. Area of the crack origination is situated on the photos on the right-hand.

$$\sigma_e = K_{th} / 1.12(\pi 7.10^{-5})^{1/2} = 3.7/0.055 = 67\text{MPa}$$

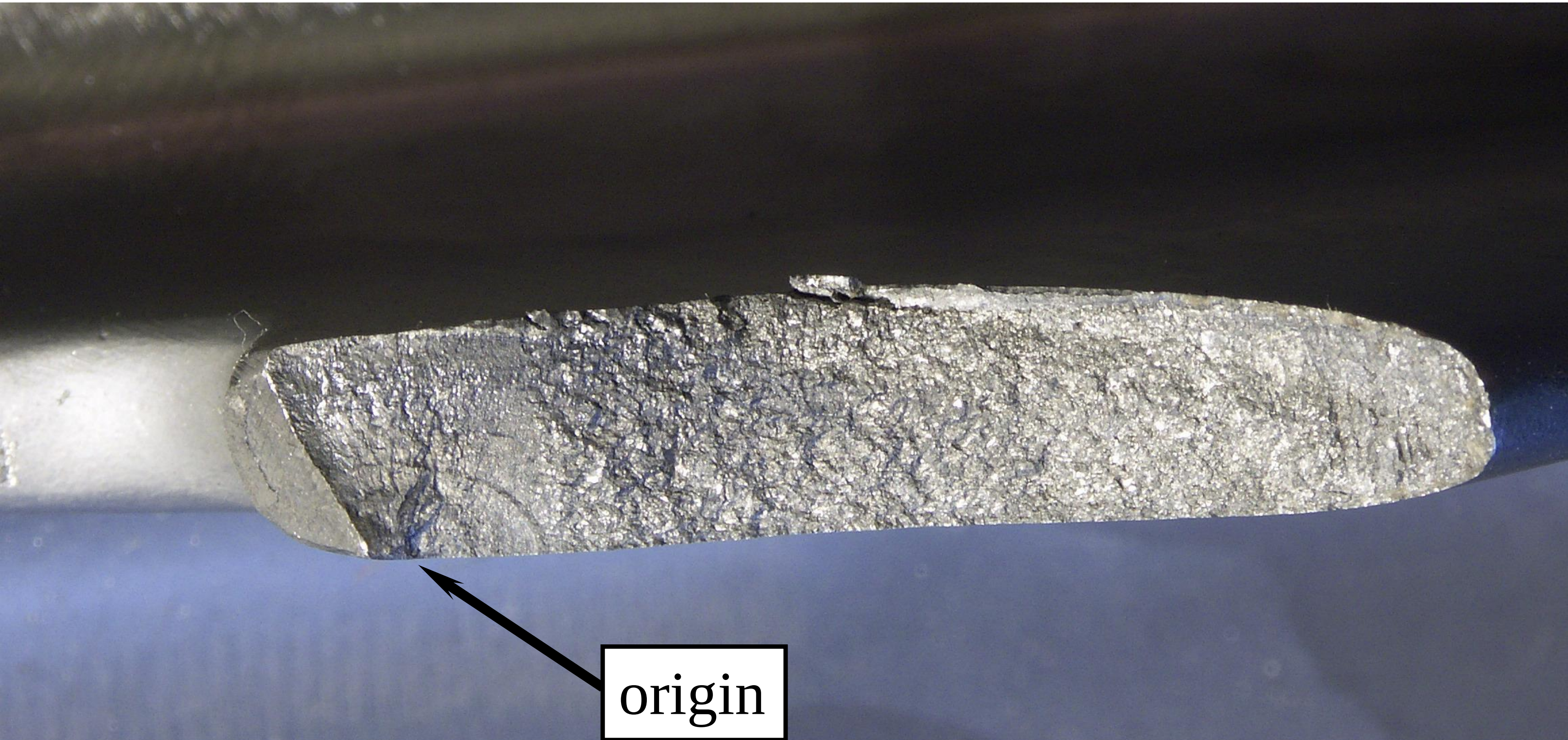
The stress intensity factor =3.7 MPa·$m^{1/2}$ for titanium alloy **VT3-1** was taken from the paper [1]. The estimated stress equivalent value of 65MPa is in four times lower than fatigue limit of the titanium alloy VT3-1. It shows that blades fatigue fracture occurred really in area of VHCF.

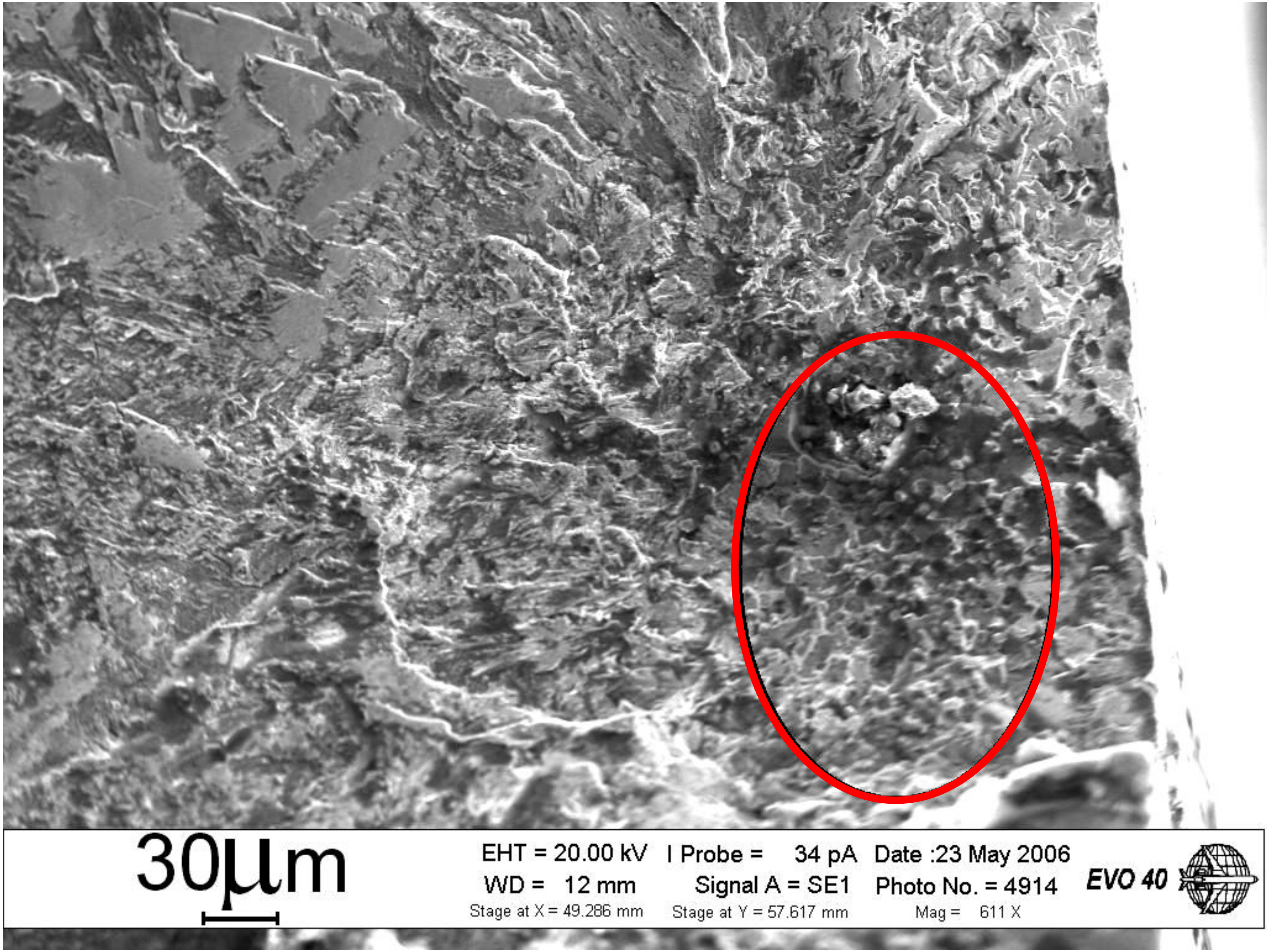
From this it follows, that, despite the intensive control and rejection of blades during repair, some of them can get into operation with sufficient depth of damage by BSs. In operating time after repair within the limits of 1500-2000 hours it is possible that blades can experience free vibrations because of the loss of contact of the BSs.

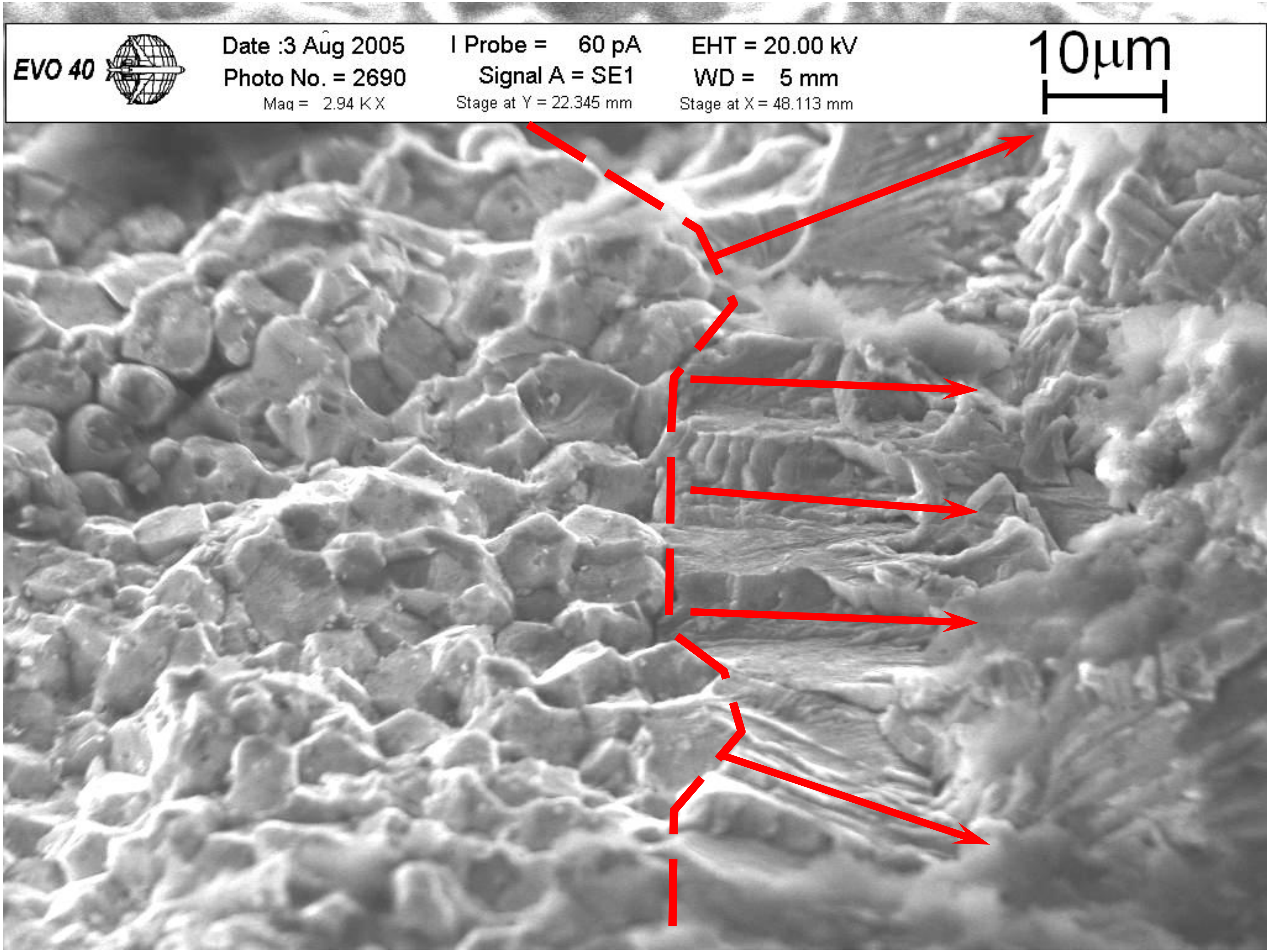


Number of cracked bandage shelves of the compressor blades of the titanium alloy **VT8** in versus (a) full and (b) after last repair lifetime to failure.

Fatigue limit of smooth specimens for titanium alloy **VT8** was determined for the number of 10^7 cycles without failure makes about 500 MPa. If it is assumed that heterogeneity inside of repaired BSs by a new technology raises the stress concentration in 5 times in area of the crack initiation, the BSs fracture at (24x5)=120 MPa should not occur at an operating time after repair approximately N_f=2500x3600x290x0.1=2.6x10^8 cycles. Especially failures should not be observed if to count, that they occur under the stress level of (7x5)=35MPa at N_f=2500x3600x3000x0.7 = 1.88x10^{10} cycles.


origin

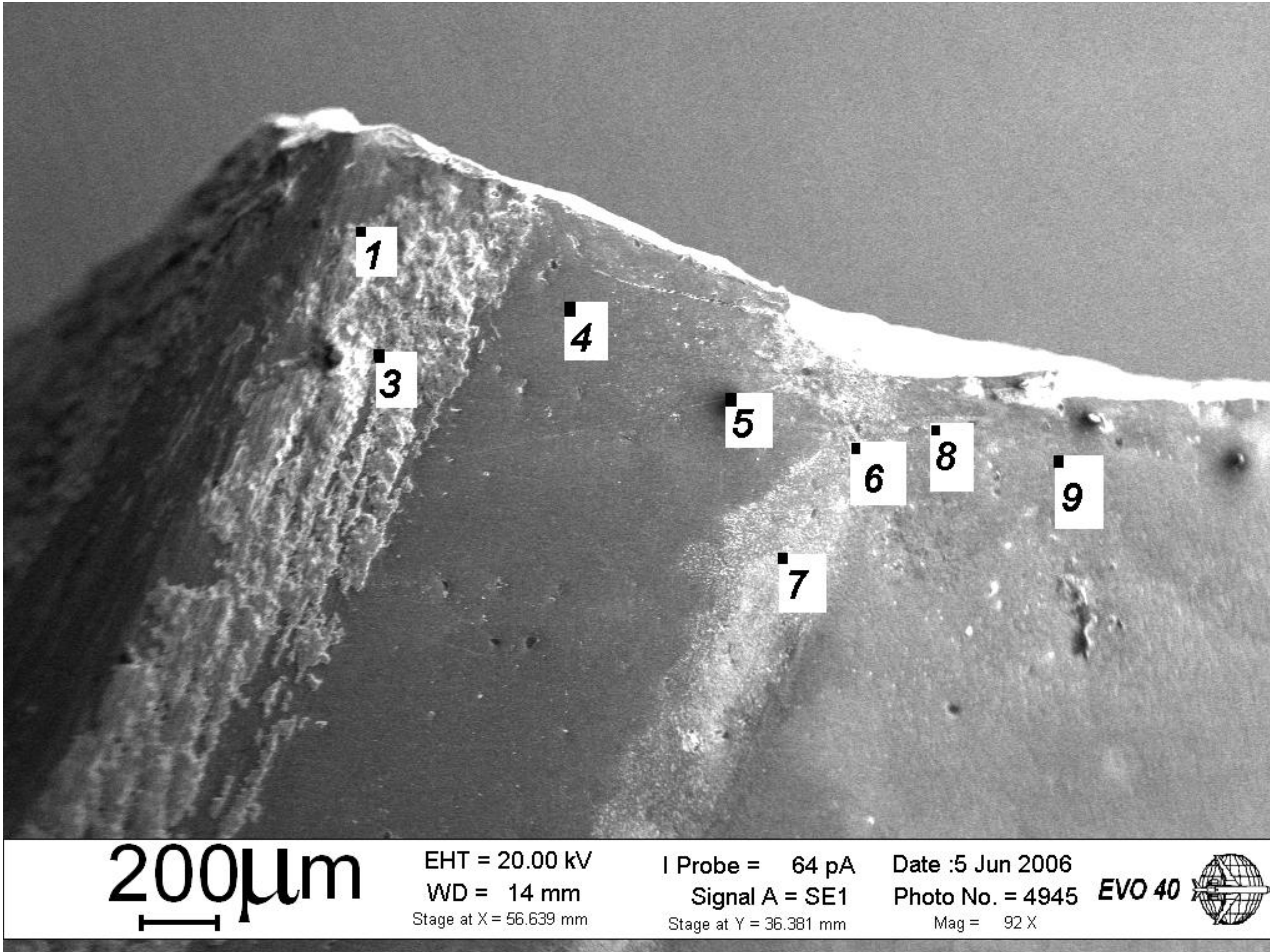

30µm
EHT = 20.00 kV
WD = 12 mm
Stage at X = 49.286 mm
I Probe = 34 pA
Signal A = SE1
Stage at Y = 57.617 mm
Date :23 May 2006
Photo No. = 4914
Mag = 611 X
EVO 40


EVO 40
Date :3 Aug 2005
Photo No. = 2690
Mag = 2.94 K X
I Probe = 60 pA
Signal A = SE1
Stage at Y = 22.345 mm
EHT = 20.00 kV
WD = 5 mm
Stage at X = 48.113 mm
10µm

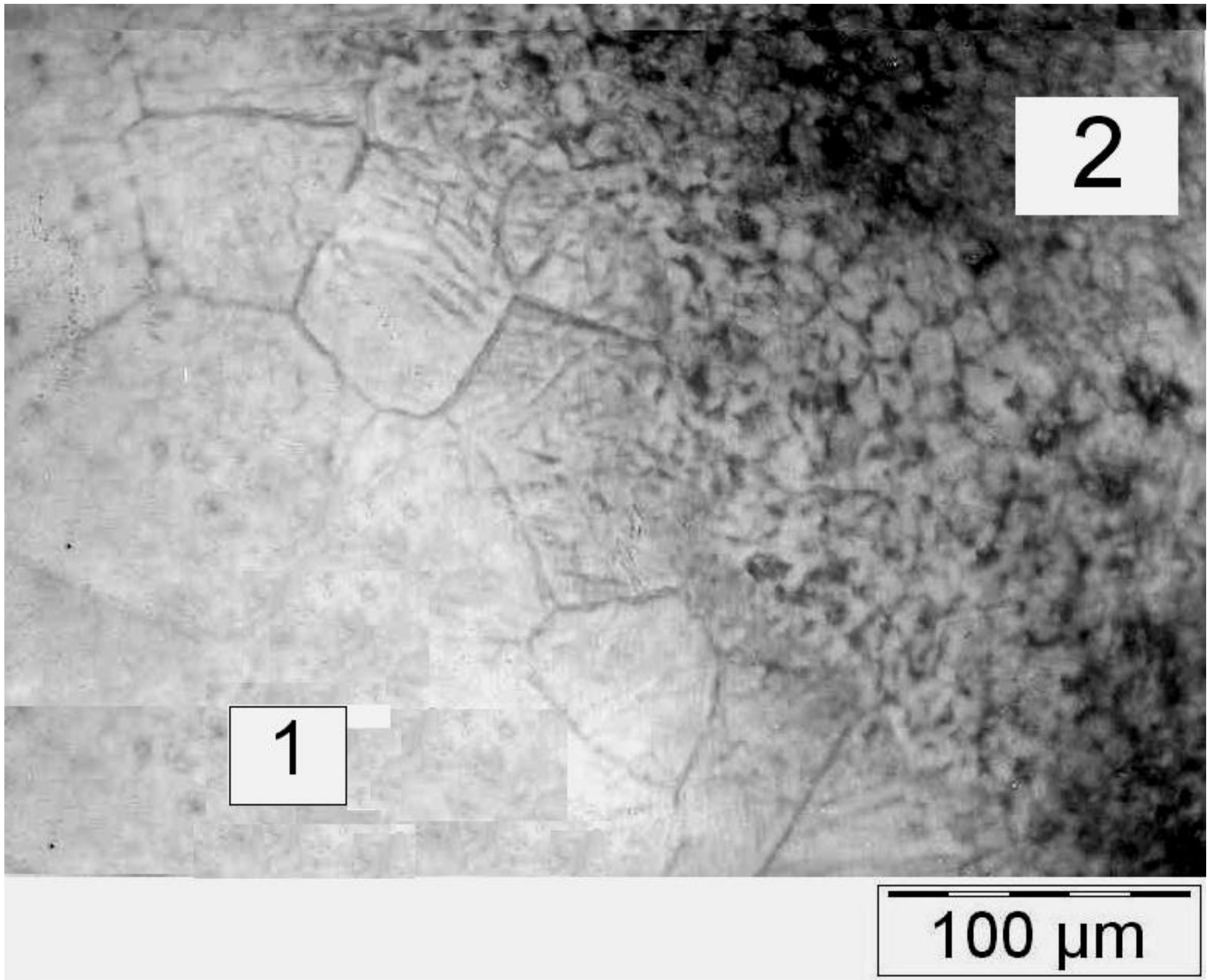
Mechanical properties and material composition of the investigated titanium alloy **VT8**

Ultimate tensile stress - 1200-1400 MPa;
Yield stress – 1100-1300 MPa.
Elongation – 20%

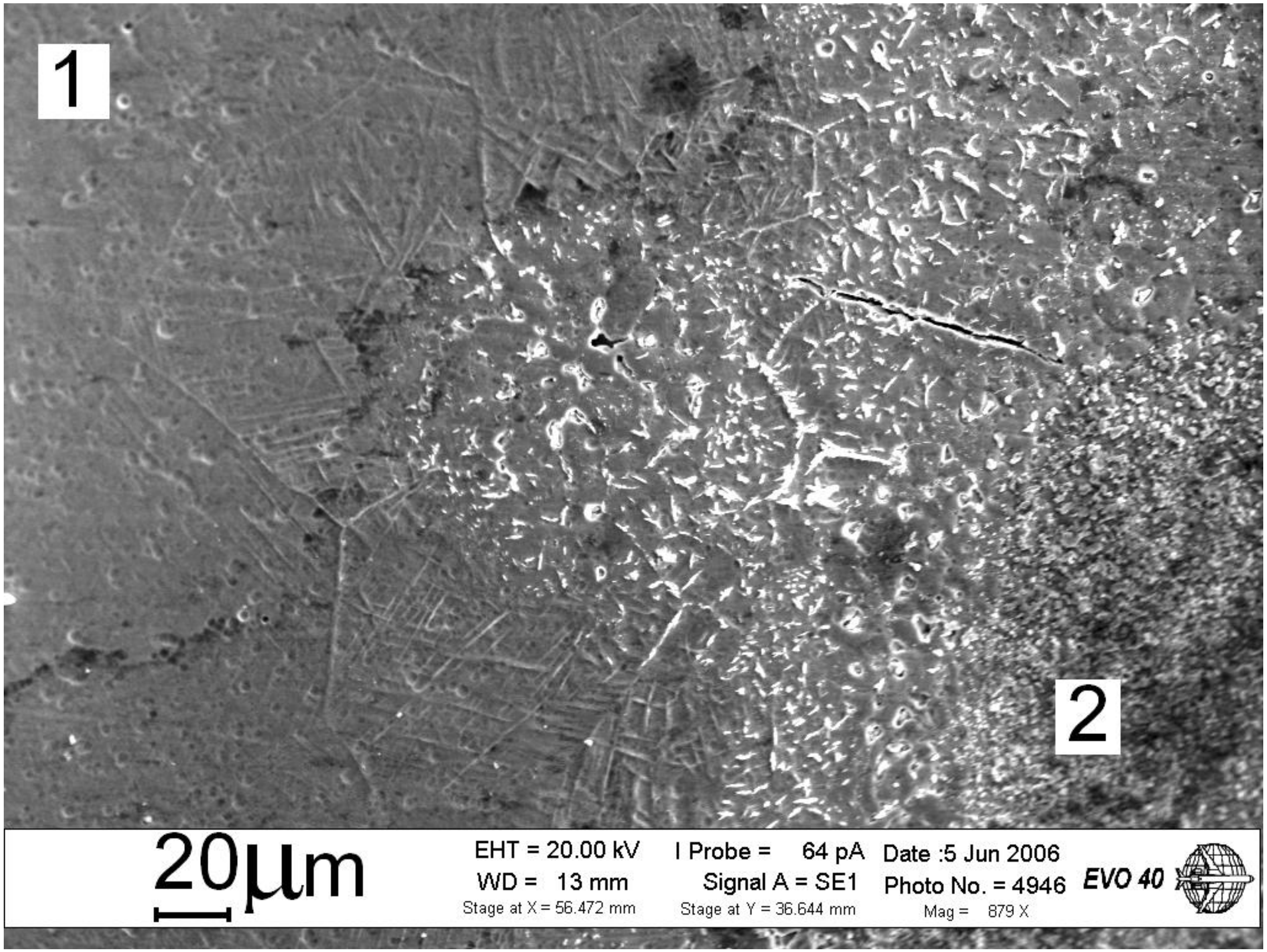
Material composition (wt%)									
Ti	Al	Mo	Si	C	Fe	Zr	O_2	N_2	H_2
Remainder	6.0-7.3	2.8-3.8	0.2-0.4	≤0.1	≤0.3	≤0.5	≤0.15	≤0.05	≤0.015

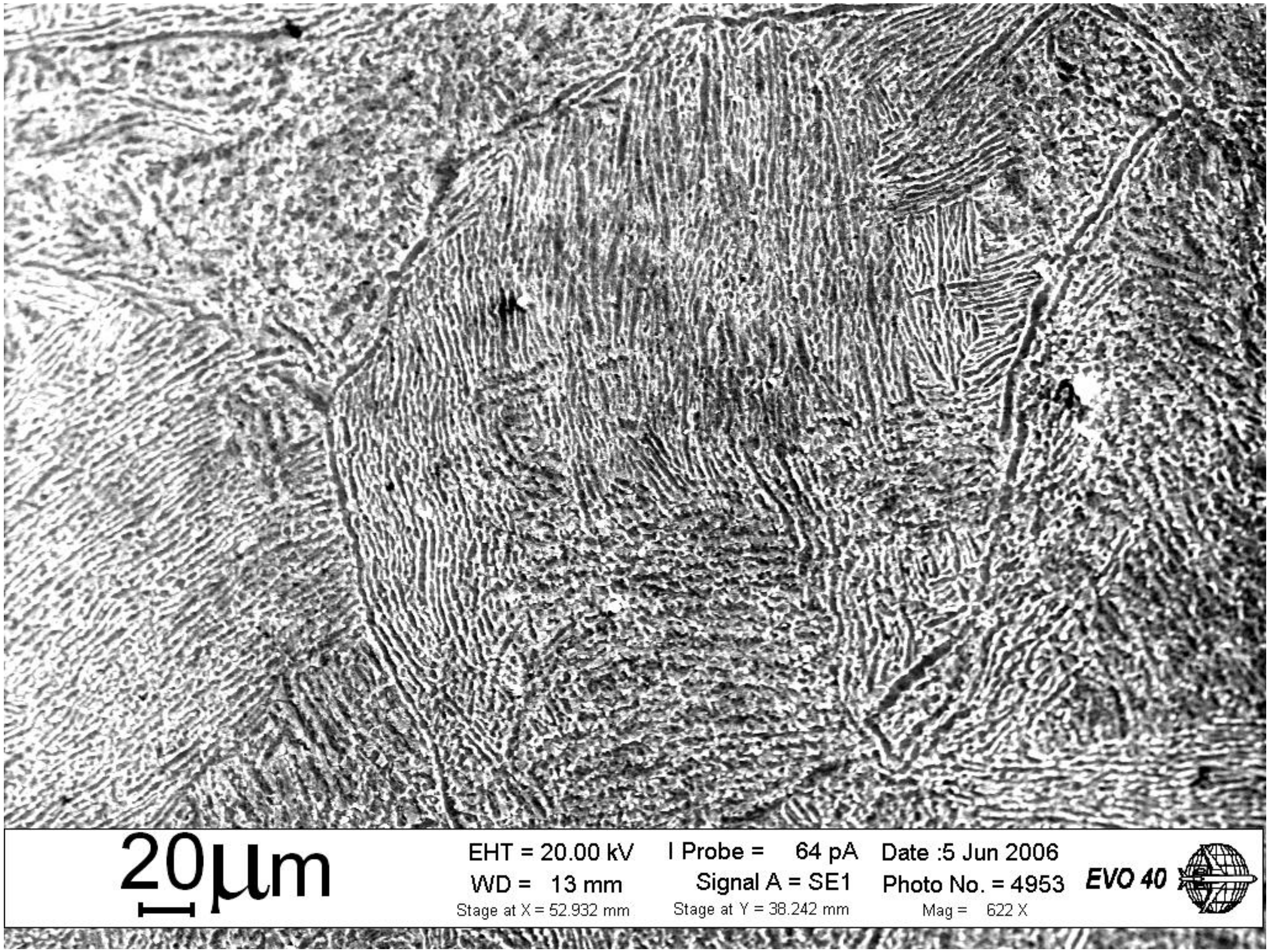

1
3
4
5
6
7
8
9
200µm
EHT = 20.00 kV
WD = 14 mm
Stage at X = 56.639 mm
I Probe = 64 pA
Signal A = SE1
Stage at Y = 36.381 mm
Date :5 Jun 2006
Photo No. = 4945
Mag = 92 X
EVO 40

	C	O	F	Mg	Al	Si	P	S	Ca	Ti	Cr	Fe	Co	Zr	Mo	Tc	Cd	Sn	W
1	11.5	14	5.7	-	-	-	-	-	0.7	4.4	0.8	0.7	9.9	-	-	1.8	13	-	38
3	15.2	4.9	1.7	-	-	-	-	-	-	0.7	-	-	9.8	-	-	2	2	-	64
4	8.4	-	-	-	6.8	-	-	-	-	75	-	-	-	3	1.6	-	-	4	1
5	51.2	16	-	-	1.7	0.3	-	0.9	-	26	-	-	-	1	-	-	1.9	1.5	-
6	7.7	6.2	-	-	4.8	-	-	-	-	58	-	-	6.0	1	2.4	-	1.0	2.1	11
7	9.0	-	-	-	4.7	-	0.3	0.6	-	58	-	-	7.2	-	-	-	-	1.5	19
8	10.9	-	1.7	-	5.0	0.5	-	-	-	79	-	-	-	-	3.5	-	-	-	-
9	10.8	6.7	-	-	4.7	0.5	-	-	-	74	-	-	-	-	3.4	-	-	-	-


2
1
100 µm


1
2
3
100µm
EHT = 20.00 kV
WD = 8 mm
Stage at X = 73.586 mm
I Probe = 64 pA
Signal A = QBSD
Stage at Y = 37.744 mm
Date :29 May 2006
Photo No. = 4942
Mag = 269 X
EVO 40


1
2
20µm
EHT = 20.00 kV
WD = 13 mm
Stage at X = 56.472 mm
I Probe = 64 pA
Signal A = SE1
Stage at Y = 36.644 mm
Date :5 Jun 2006
Photo No. = 4946
Mag = 879 X
EVO 40


20µm
EHT = 20.00 kV
WD = 13 mm
Stage at X = 52.932 mm
I Probe = 64 pA
Signal A = SE1
Stage at Y = 38.242 mm
Date :5 Jun 2006
Photo No. = 4953
Mag = 622 X
EVO 40

$$\sigma_w = [(3.09 - 0.12 Ln N_f)(HV + 120)] / (\sqrt{area})^{1/6}$$

Hardness of the mentioned above composition "CT4-VK15-VT8" cannot be determined with high reliability as the zone has small extent. Nevertheless, the estimation of hardness can be given from conditions of measurement along a fusion zone for material composition CT4-VK15. Because of such measurements it has been revealed, that hardness HV= 280 Kgf/mm2. The area of the crack origin makes *area* =619888.8 μm^2, i.e. = 787 microns. Using the specified values of parameters of the equation (2), we receive for different in-service lifetimes:

$$\begin{cases} [(3.09 - 0.12 Ln 2.6 x 10^8)]400/2.52 = 320 MPa \\ [(3.09 - 0.12 Ln 1.88 x 10^{10})]400/2.52 = 260 MPa \end{cases}$$

Conclusions

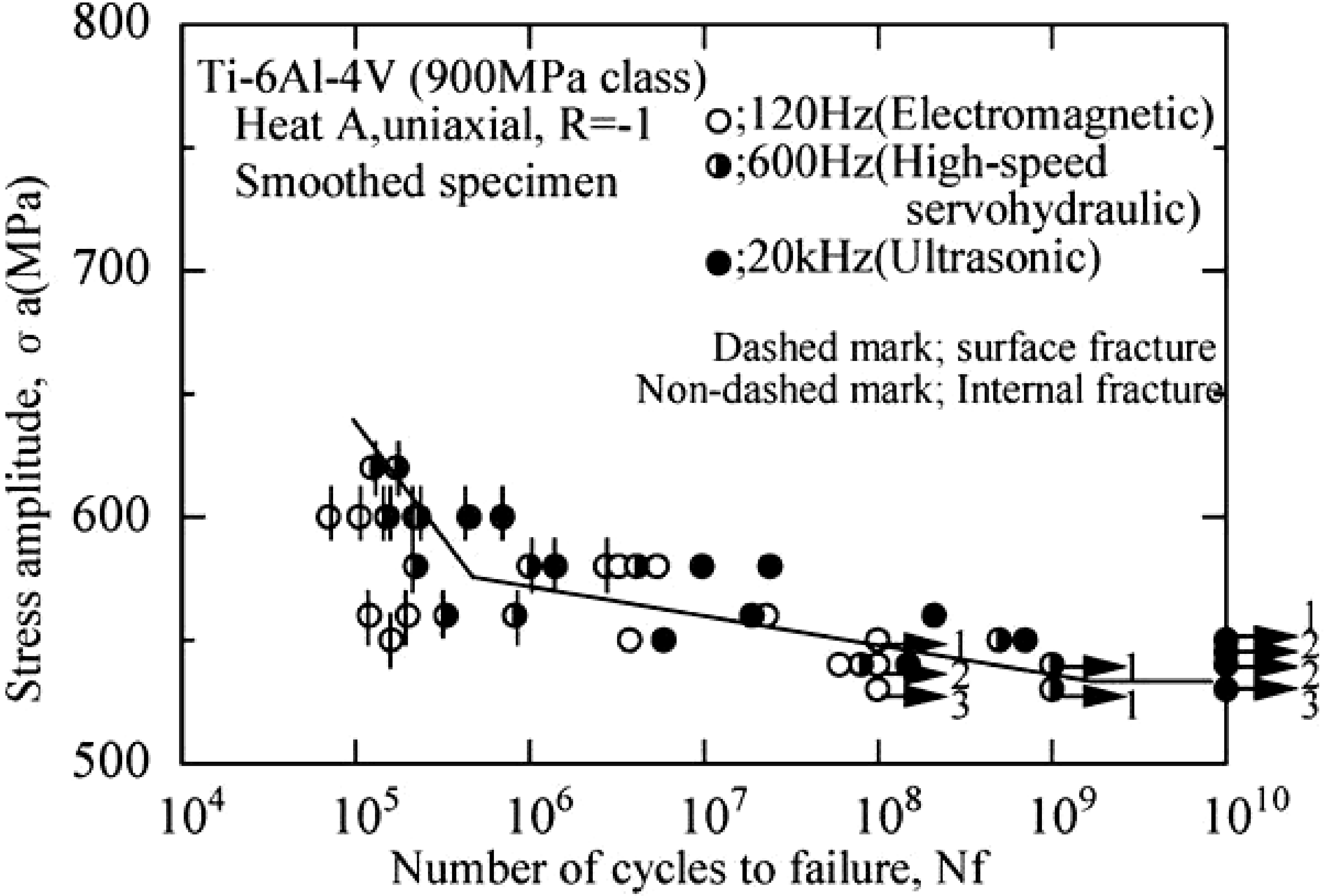
The discussed results of BSs investigations allowed to us to conclude, that the main cause of BSs fatigue fracture in operation conditions is connected to their high stress-state in the transition area of CT4-VT8. Any variations of material properties inside of the area CT4-VT8 or, especially, constructed bad transition area CT4-VK15-VT8 directed to fatigue cracking of BSs at an operating time after repair not more than 2500 hours.

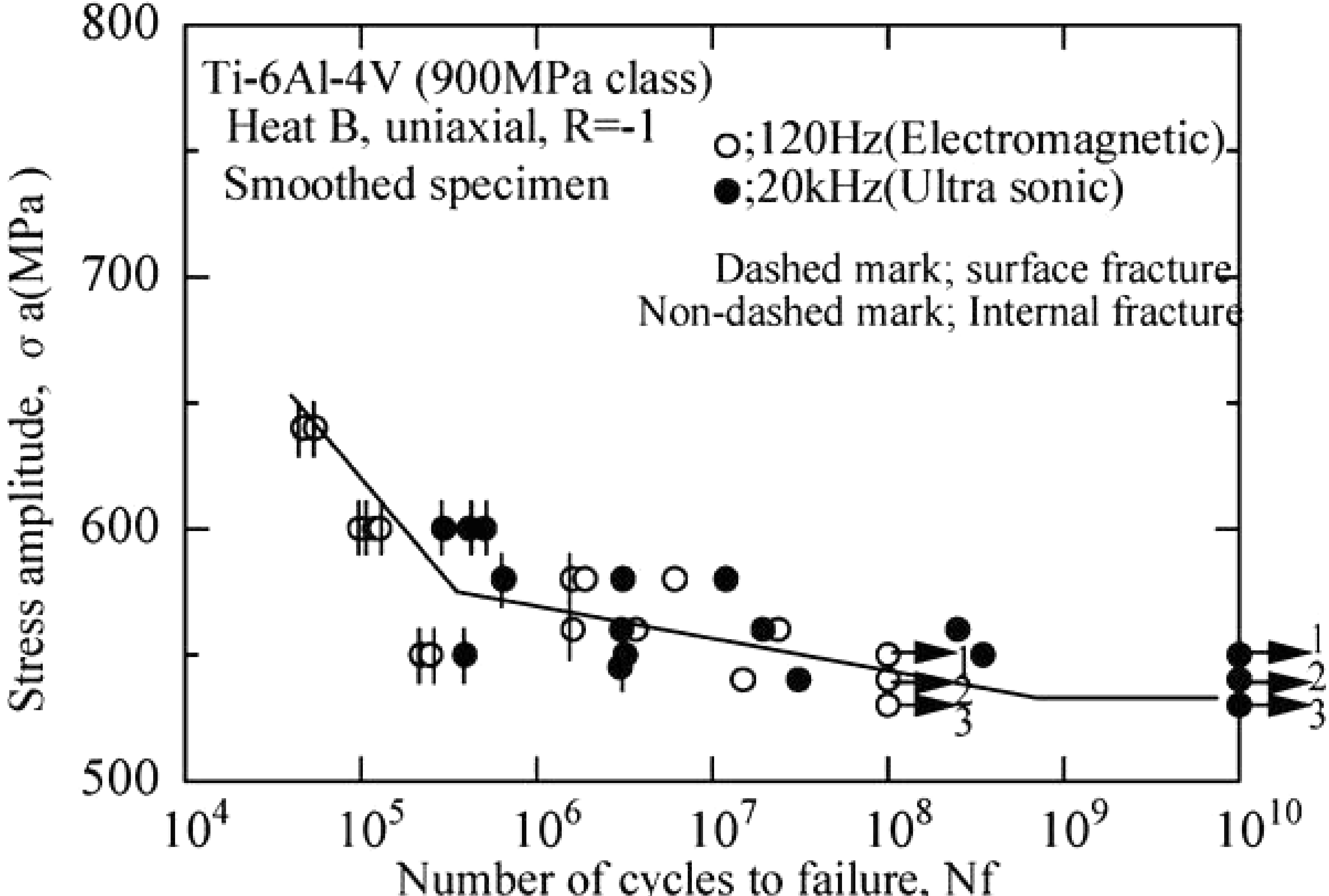
For the BSs of the low-pressure compressor of the engine Nk-8-2u was recommended to provide stability of material properties in area of the composition CT4-VT8, not supposing introducing in a layer between them of the material VK15.

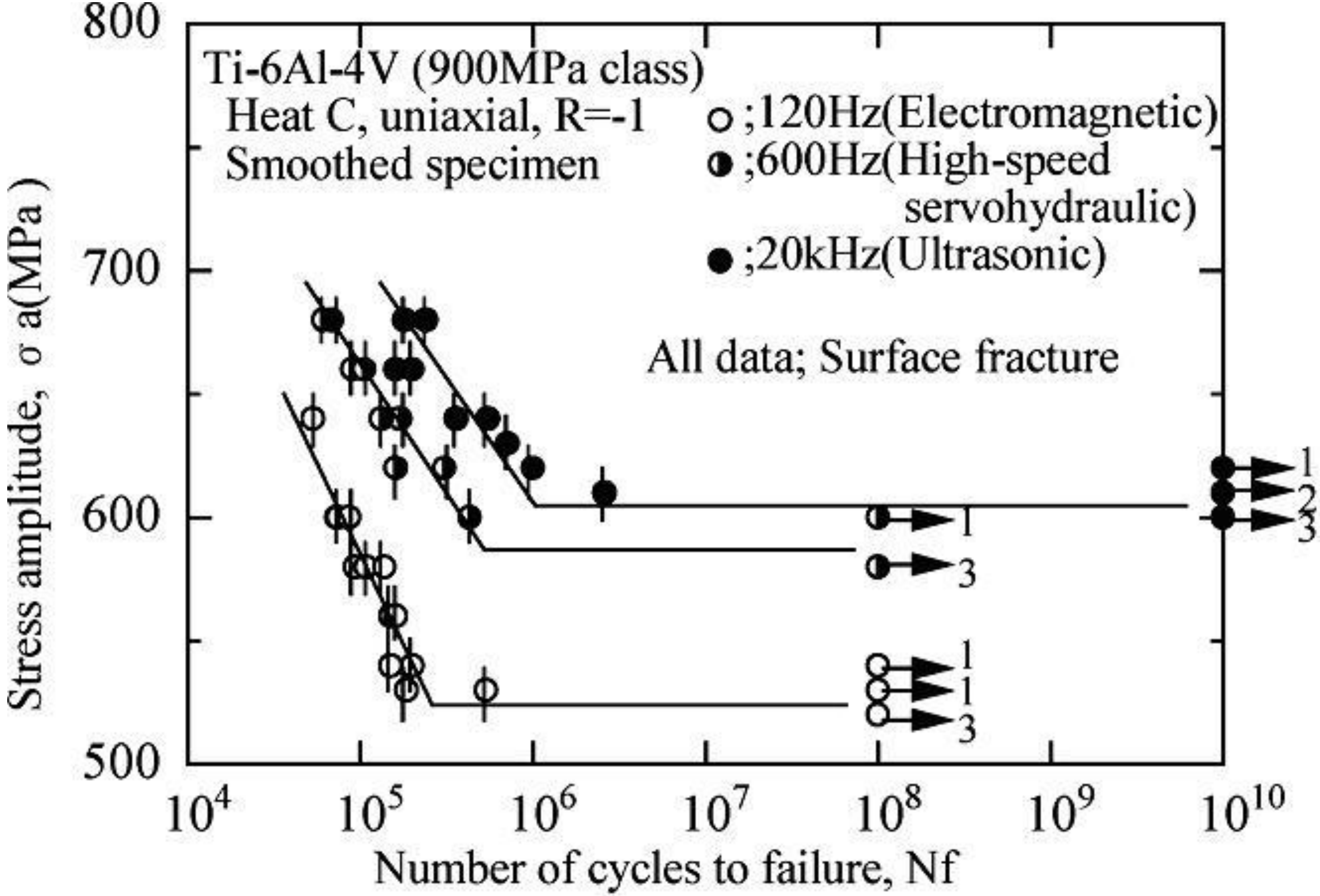
Solution Aging: 930/60 min, air cooled 705/120 min, air cooled (E. TAKEUCHI, Y. FURUYA, N. NAGASHIMA and S. MATSUOKA, 2008)

Heat	0.2%	Предел прочн.	Удлинение	Сужение	Шарпи	HV
A	916	960	21	45	32	326
B	897	967	18	42	43	319
C	866	906	23	56	36	319

Heat	Al	V	Fe	C	N	H	O
A	6.27	4.30	0.21	0.016	0.0055	0.0048	0.18
B	6.39	4.31	0.18	0.012	0.0058	0.0120	0.17
C	6.11	4.39	0.17	0.004	0.0034	0.0074	0.17


Ti-6Al-4V (900MPa class)
Heat A,uniaxial, R=-1
Smoothed specimen
○;120Hz(Electromagnetic)
◐;600Hz(High-speed servohydraulic)
●;20kHz(Ultrasonic)
Dashed mark; surface fracture
Non-dashed mark; Internal fracture
800
700
600
500
Stress amplitude, σ a(MPa)
10^4
10^5
10^6
10^7
10^8
10^9
10^10
Number of cycles to failure, Nf
1
2
3


Ti-6Al-4V (900MPa class)
Heat B, uniaxial, R=-1
Smoothed specimen
○;120Hz(Electromagnetic)
●;20kHz(Ultra sonic)
Dashed mark; surface fracture
Non-dashed mark; Internal fracture
Stress amplitude, σ a(MPa)
Number of cycles to failure, Nf
800
700
600
500
10^4
10^5
10^6
10^7
10^8
10^9
10^10
1
2
3



Ti-6Al-4V (900MPa class)
Heat C, uniaxial, R=-1
Smoothed specimen
;120Hz(Electromagnetic)
;600Hz(High-speed servohydraulic)
;20kHz(Ultrasonic)
All data; Surface fracture
Stress amplitude, σ a(MPa)
Number of cycles to failure, Nf
800
700
600
500
10^4
10^5
10^6
10^7
10^8
10^9
10^10
1
2
3