MANHIRP

Integrating Process Controls with Manufacturing to Produce High Integrity Rotating Parts for Modern Gas Turbines

Presentation to RISC/RoMan

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MANHIRP: General Progress

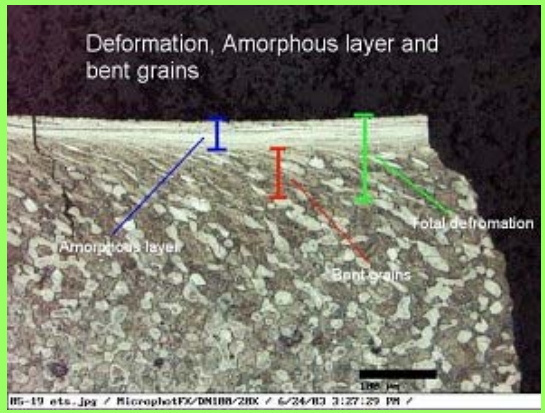
- Project started in February 2001
- Originally due to finish 31st January 2005
  - Extension requested for 6 months at no increase of costs
  - Needed to allow completion of fatigue testing and assimilation of results
  - Awaiting decision of CEC over extension request
- No similar follow-on project is planned at the moment
  - Possibility of limited project on practical implementation of process monitoring techniques which would not be for general release to industry
  - Position will be reviewed again before completion of project

Description of work in last year

- **Creation, detection and testing of anomalies (1st presentation)**
  - **Holemaking**
  - **Turning**
  - **Broaching**
    - **All on two materials, Inco 718 & Ti 6/4**
- Developments in NDI (2nd presentation)
- Developments in process monitoring (3rd presentation)

Holemaking in Ti 6/4

- The anomalies tested in Batch 1 and 2 are:-
  - Smearing (e.g. chips)
  - Amorphous layer (due to heat and mechanical deformation)
  - Bent grains (small mechanical deformation without heat)
  - Scratches
  - Surface roughness
- In practice these types may occur in combination

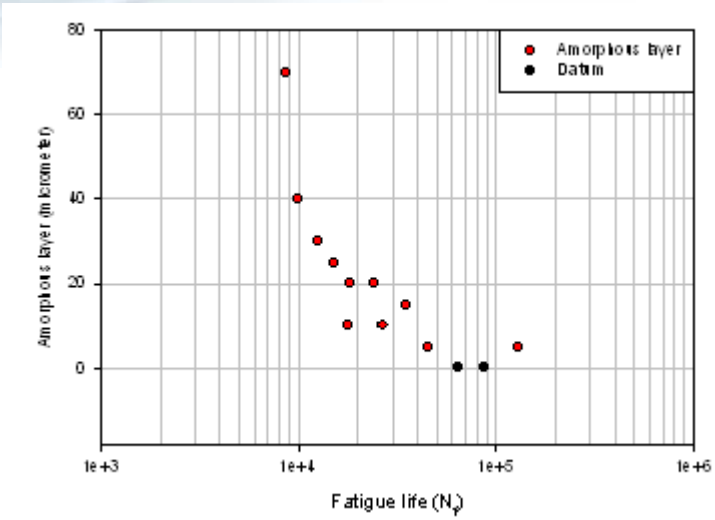


Anomaly produced during drilling containing amorphous layer and bent grains.

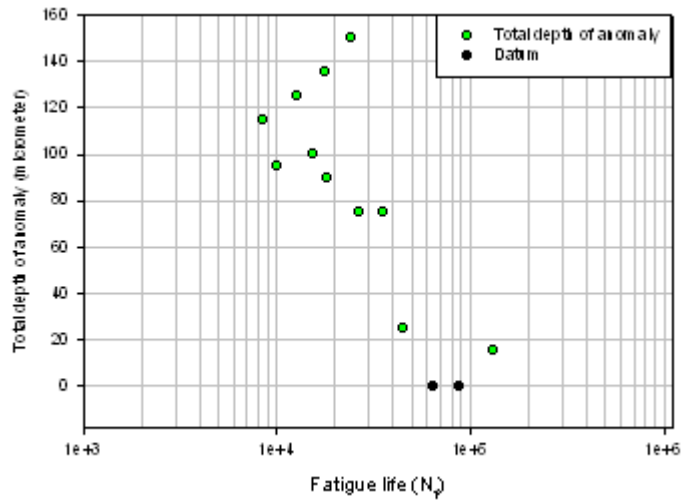
Vickers hardness indentations within the amorphous layer and adjacent material.

Fatigue testing of Ti 6/4

All tests at single stress level



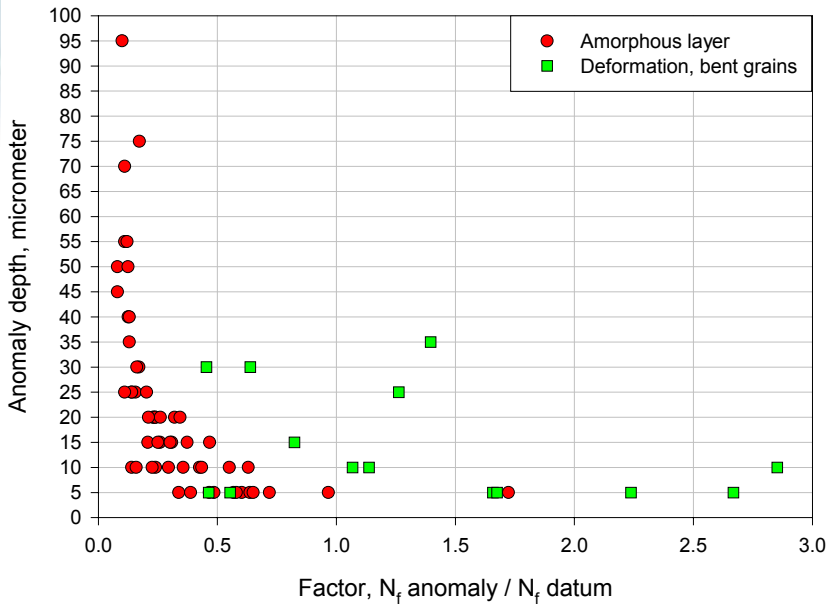
Amorphous layer vs. Fatigue life deficit



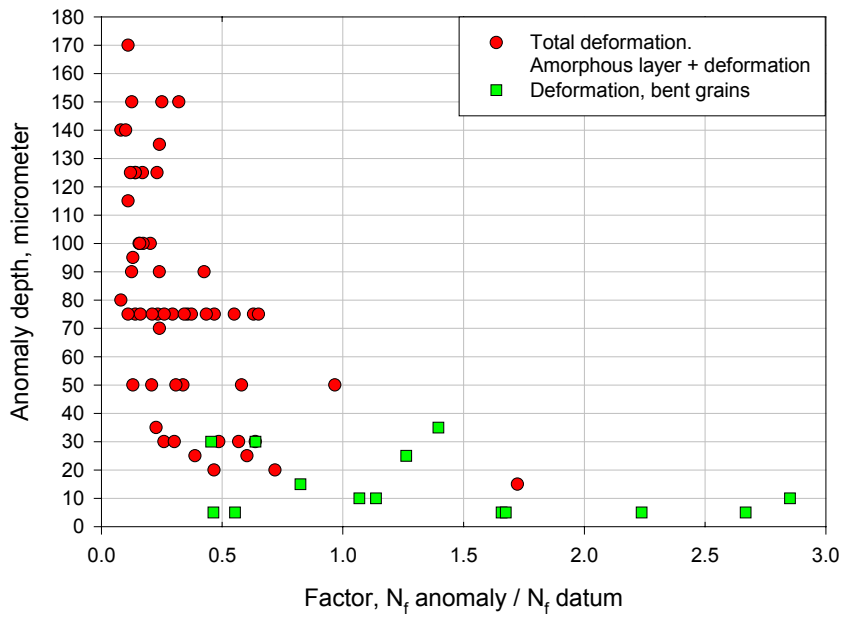
Total depth (= Amorphous layer + bent grain) vs. Fatigue life deficit

- There is less scatter when plotted against amorphous layer
  - All specimens had both amorphous layer and bent grain

Bent grain vs. Amorphous layer



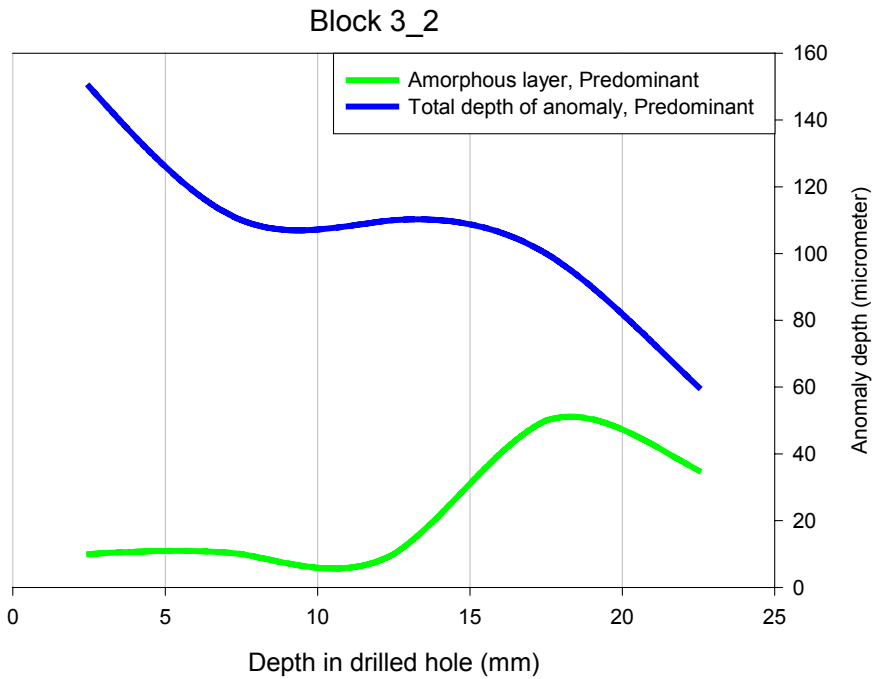
Amorphous layer vs. Fatigue life deficit



Total depth (= Amorphous layer + bent grain) vs. Fatigue life deficit

- Amorphous layer is associated with greater depths of anomaly
- Lives for just bent grain may not differ substantially from datum

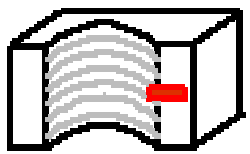
Anomaly size against depth

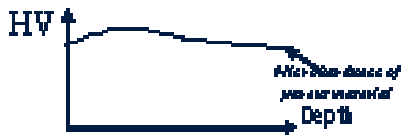


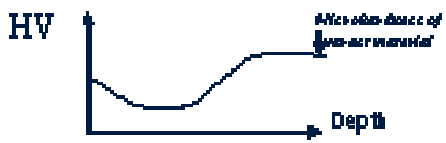
- Anomaly is largest in holes at either end
  - Total depth is largest near drill entry
  - Amorphous layer depth is largest near drill exit

Holemaking in Inco 718

- Three types of anomaly developed:-







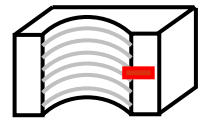
(a) (b) (c)

(a): isolated smearing; (b) continuous smearing; (c) heat affected zone.

No HAZ

Description of anomalies

- *The three types of microstructural anomalies*

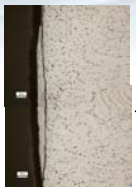


→Isolated Smearing (IS)

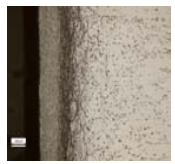
→Continuous Smearing (CS)

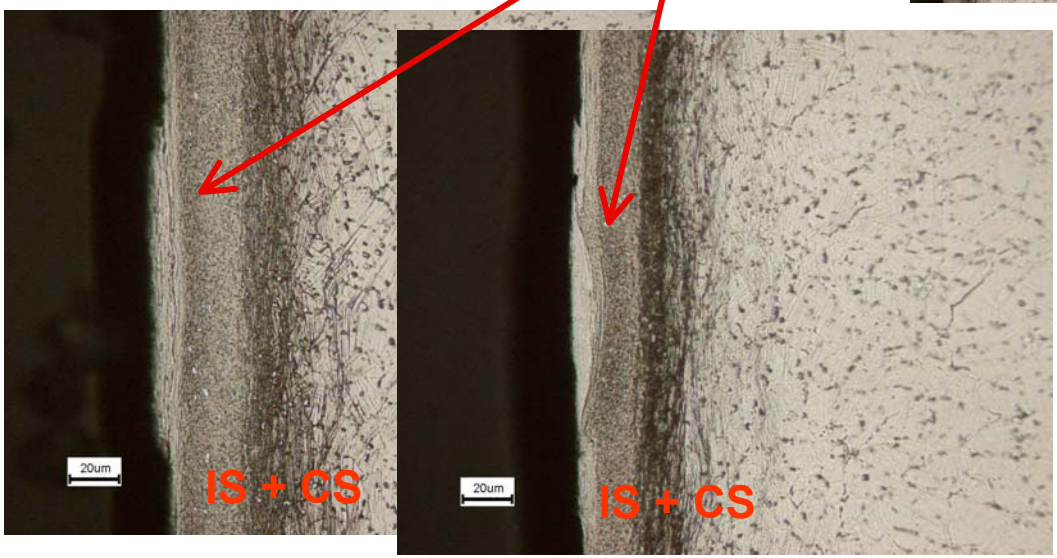
Redeposited layer

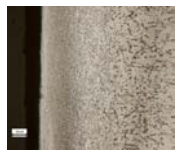
→Heat Affected Zone (HAZ)



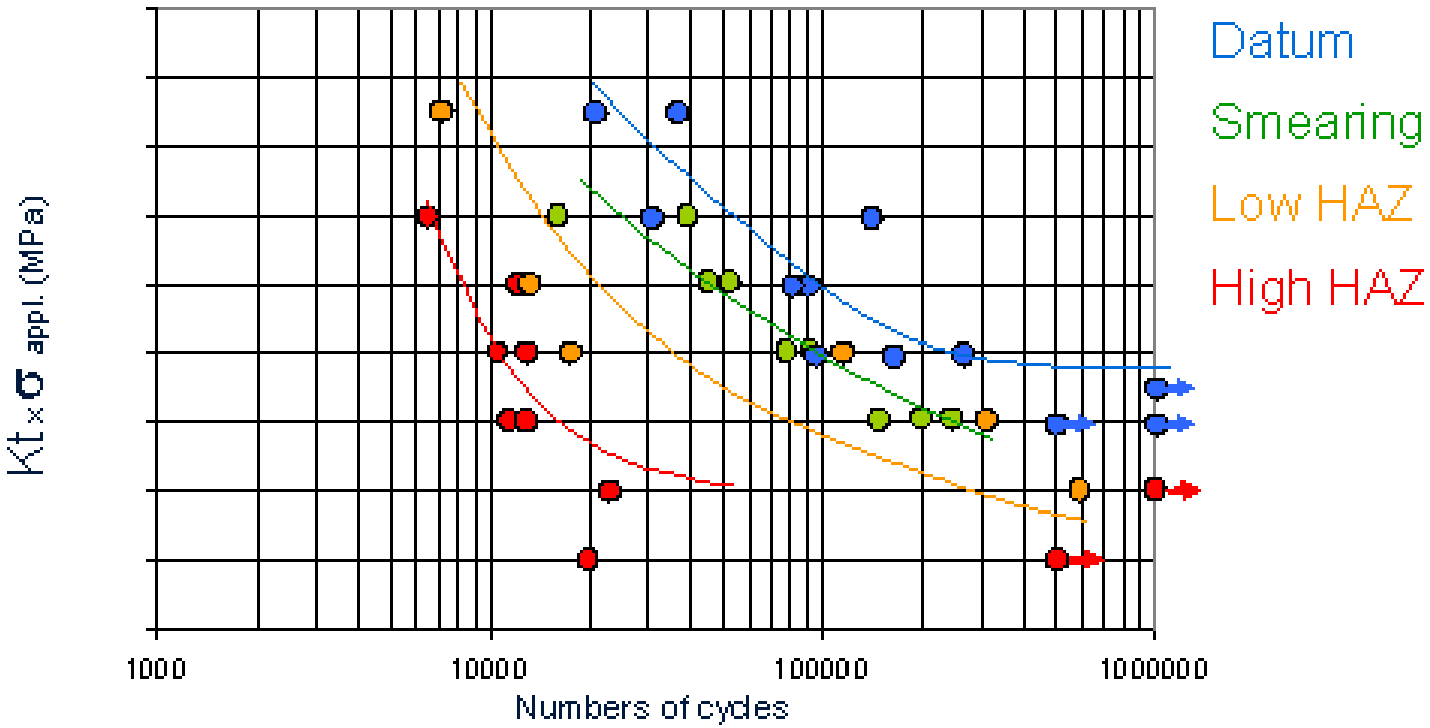
IS + CS







Fatigue performance of 3 anomaly types



- Note increased scatter as depth of anomaly increases
  - Could be just effect of fatigue limit
- Isolated smearing (green line) shows only marginal reduction compared to datum when not associated with HAZ
- High HAZ (red line) has chip embedded (main effect)

Effect of reaming after drilling

TMP
With coolant

7mm diameter
8,5mm depth

HIGH HAZ
Without coolant

Increase of radius is 0.3 mm (≅0.012”)

Operation of reaming	*coolant*	*Increase of diameter (mm)*
1st reaming	Y	7,3
2nd reaming	Y	7,6

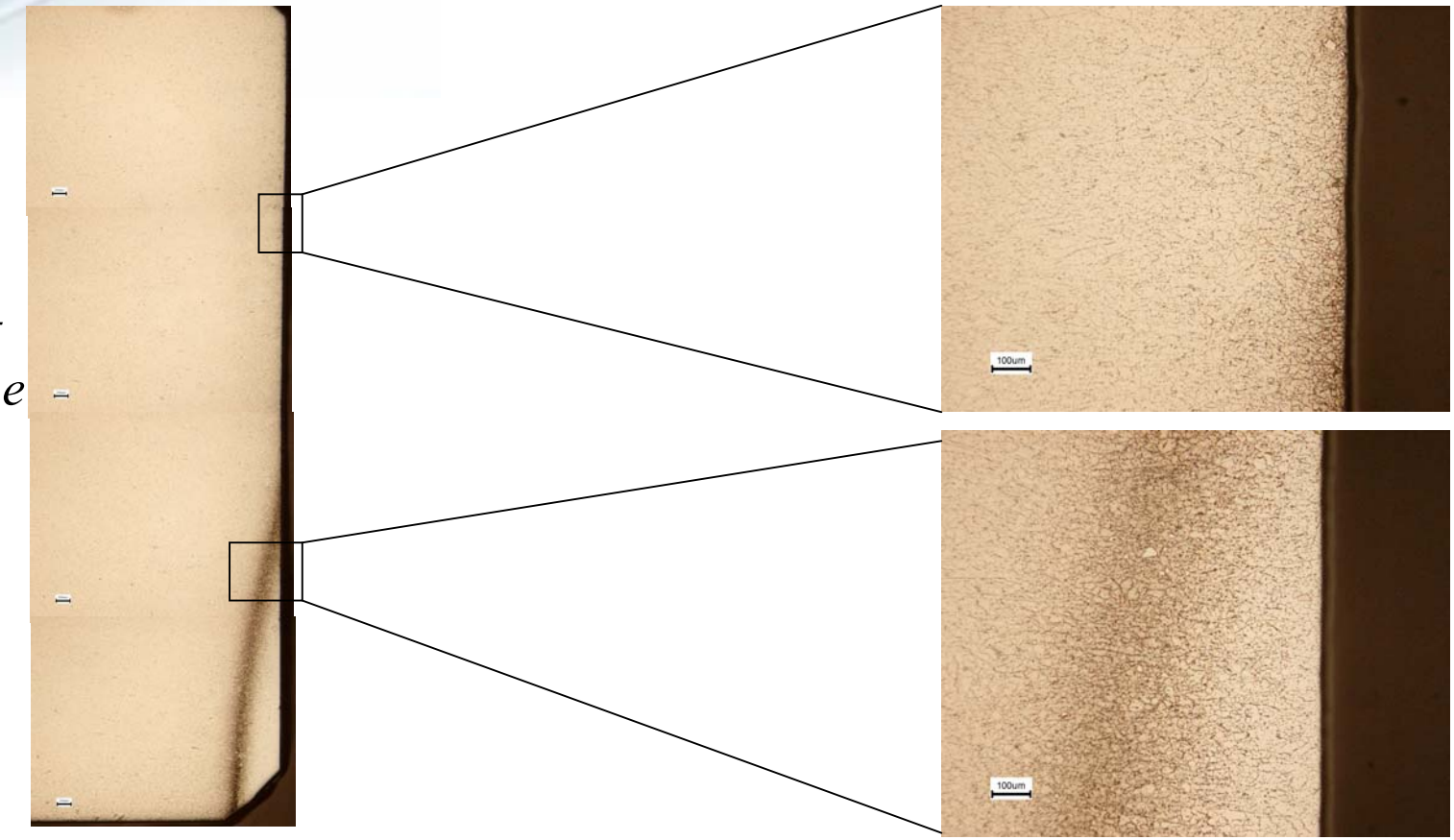
All geometric anomalies are removed on the hole surface

Reaming can remove anomalies on surface

All geometric anomalies are drilled out on the hole surface

Example :

Hole with
Continous smearing
and heat affected zone
+
reaming

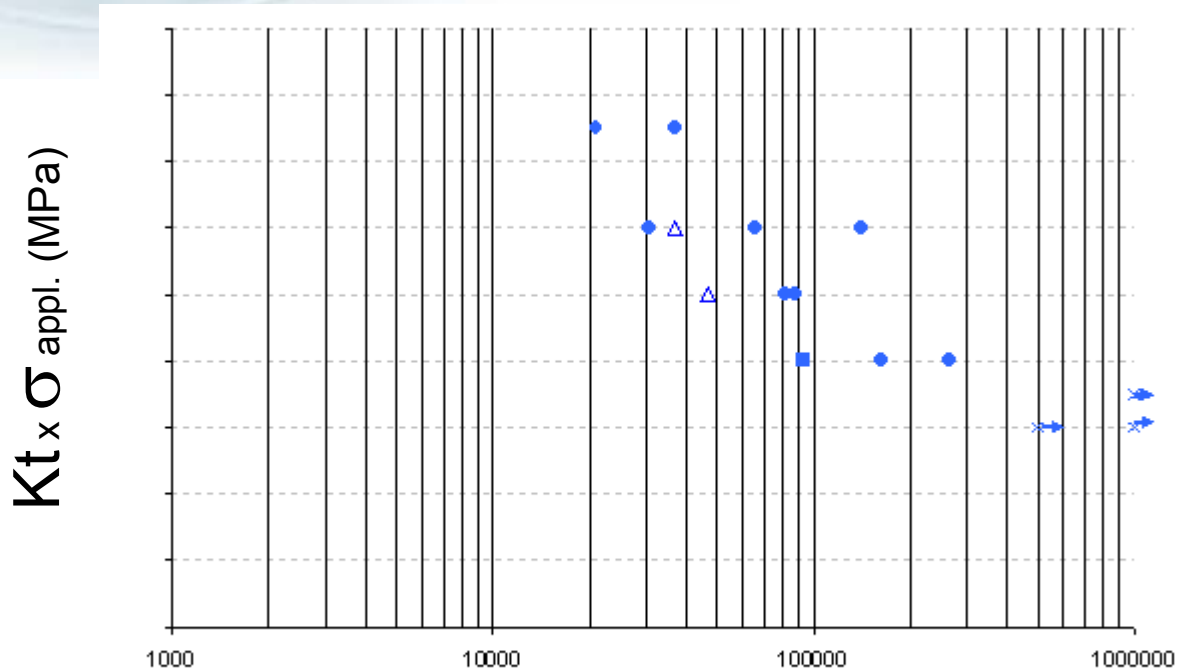


Fatigue effects of reaming – good surface

Fatigue tests in progress for reaming holes

TMP

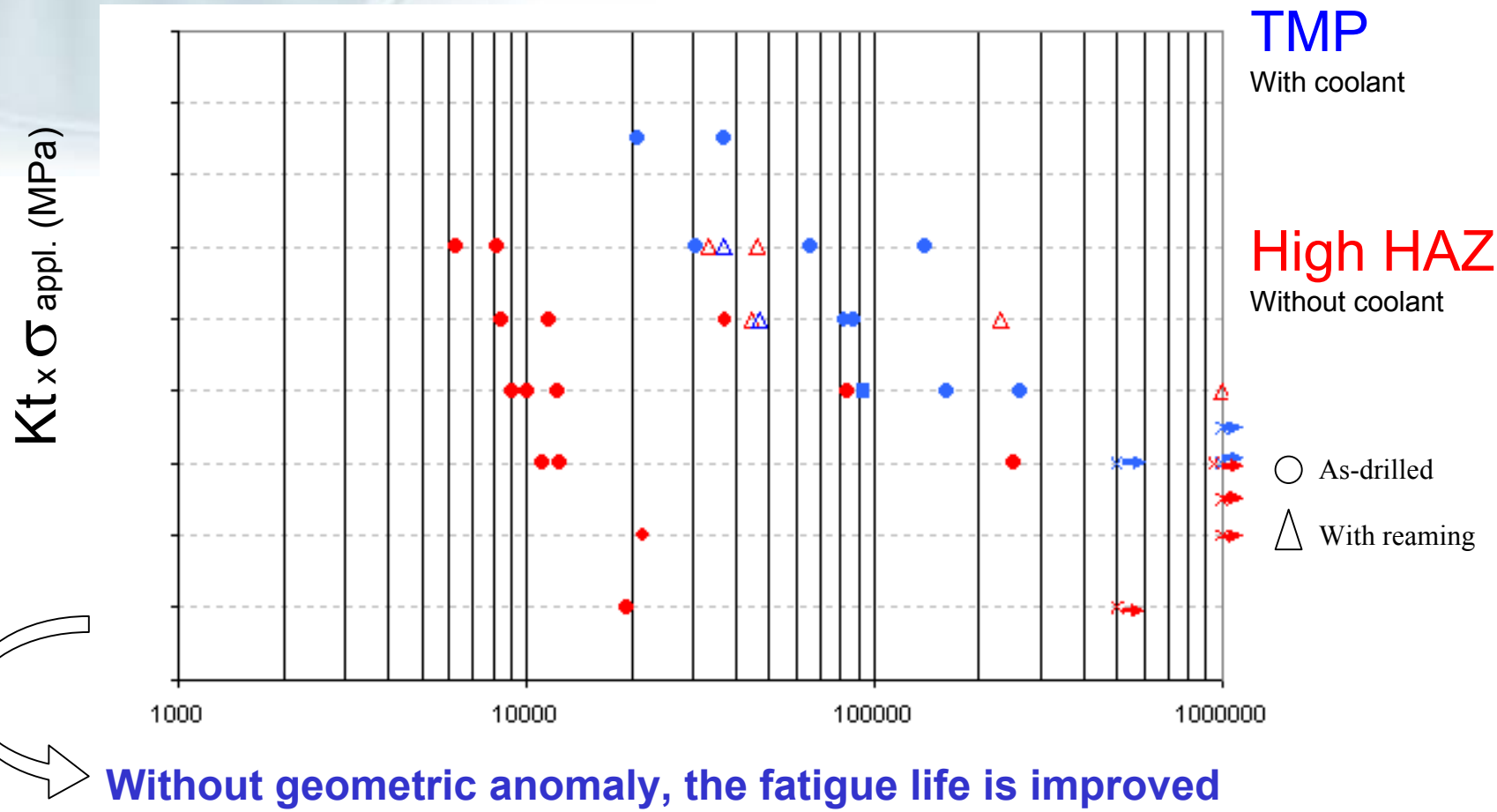
With coolant



○ As-drilled

△ With regrinding

Fatigue effects of reaming – anomalous surface



Without geometric anomaly, the fatigue life is improved

Conclusions on fatigue of holes with anomalies

- In Titanium
  - Depth of amorphous layer seems to provide better correlation and less scatter
  - Arguable that bent grain without amorphous layer may:-
    - Not change mean life
    - Increase scatter
    - But insufficient evidence to be certain
- In Nickel still waiting coupling of data on cut-up examination and fatigue results
- Reaming which removes sufficient depth restores (improves?) fatigue behaviour
  - Provided it doesn't introduce further anomalies

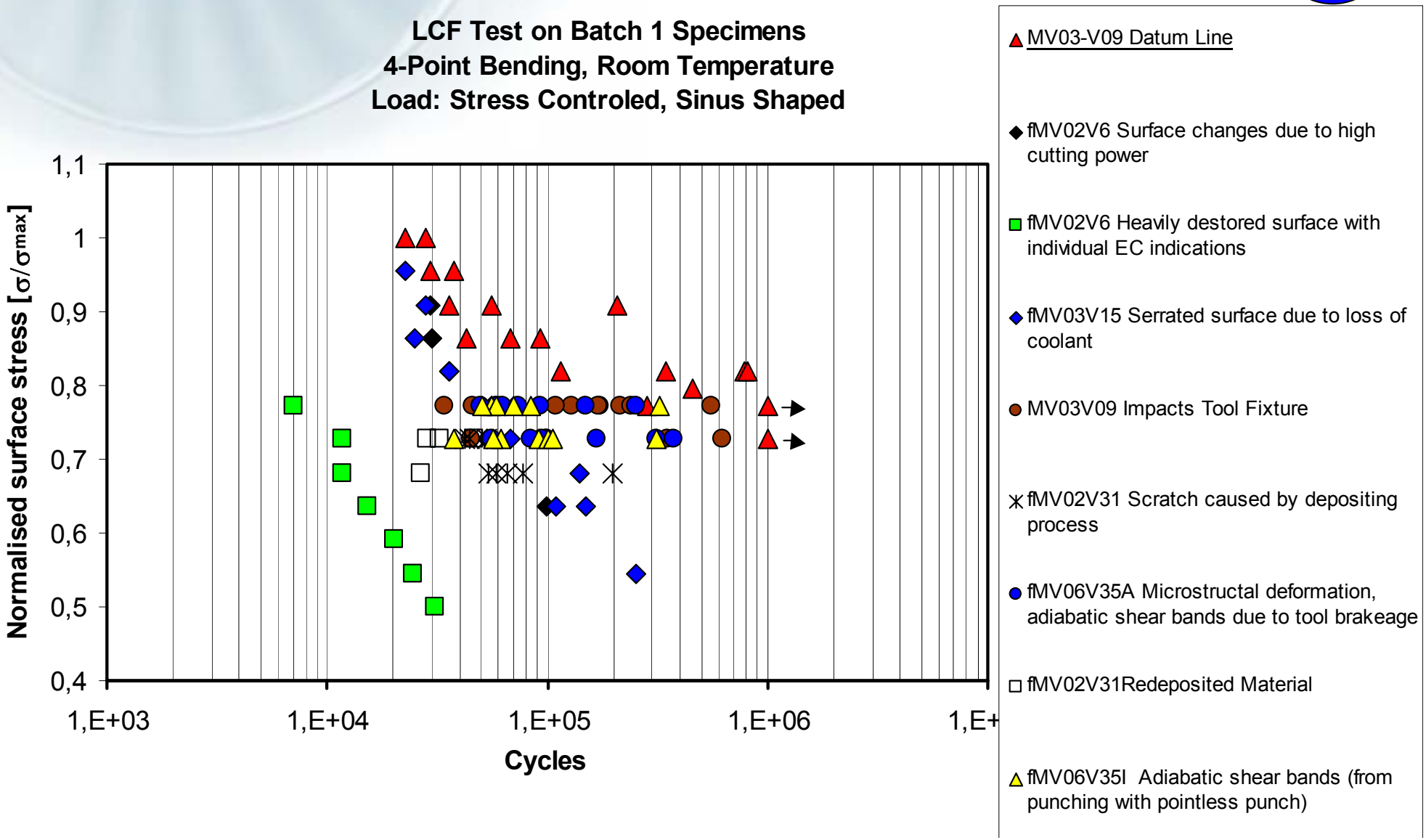
Turning in Titanium

- A number of specimens reported previously had failed from the edge corner of the specimen
  - Implication is that this may only be a lower bound to actual capability of datum turned surface
- Hence design of specimen modified:-
  - Edges chamfered back
  - Polished corners
  - Shot peened to prevent crack initiation
- New design fails on turned surface and not corners

Created anomaly types or artificially produced by or after turning Ti 64:

- Re-depositing or smearing of parent material
- Heavily distorted surface by contact with tool fixture during turning
- Heavily distorted surface after rework
- Chatter marks
- Orange peel
- Serrated surface due to loss of coolant
- Surface changes due to high cutting power
- Microstructural deformation, residual stress and adiabatic shear bands from tool breakage

Turning in Titanium: Overview Batch 1



Conclusions for Batch 1

Evaluation of LCF-tested datum line and some of the anomaly specimens show that crack initiation took place at the edge of cross section.
(96 specimens tested in batch1)

Effect on LCF-results

- the real life of the undamaged sample can be expected higher
- in some cases the LCF-result might be:

"*the anomaly is not worse than the edge effect*"

Remedy:

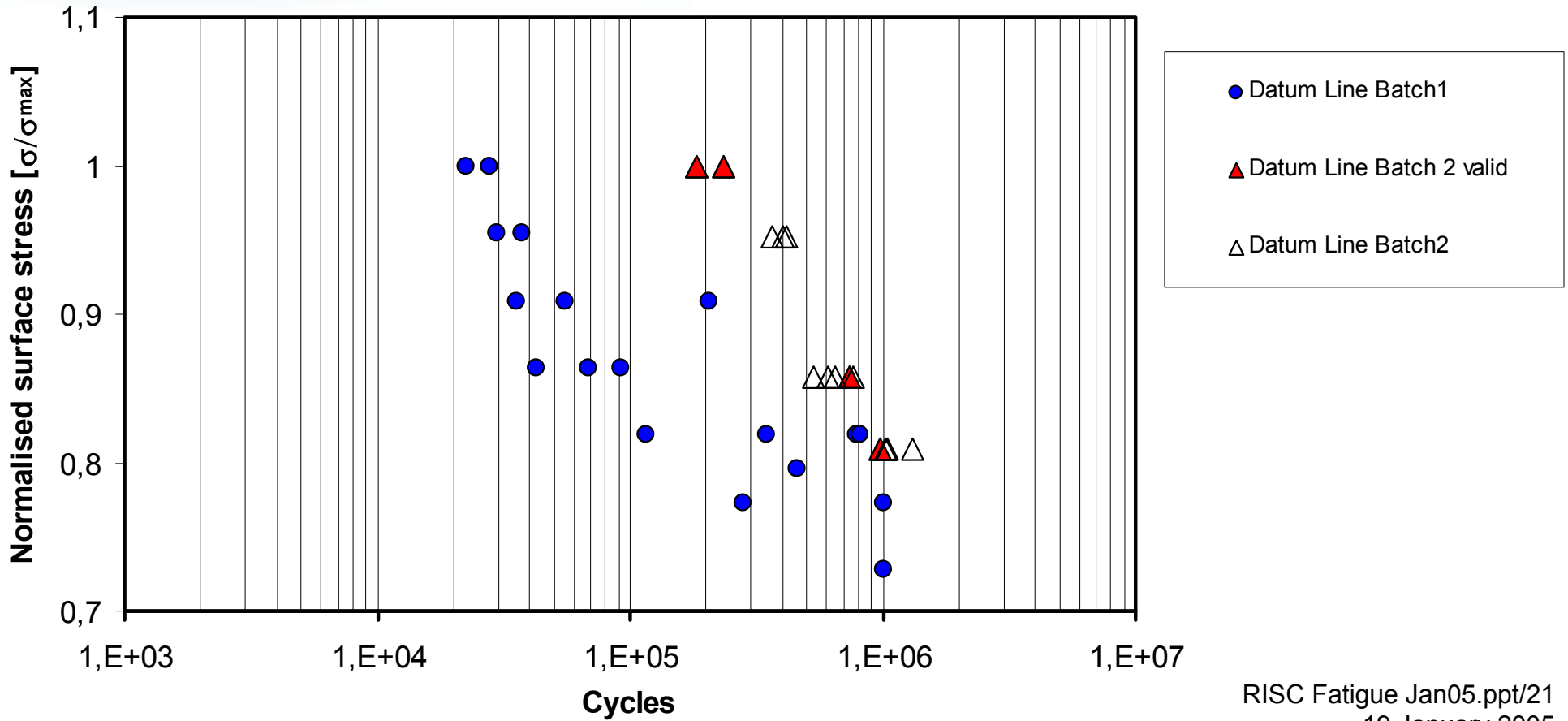
- Redesign of specimen shape and repetition of datum line and some key LCF tests.
- Batch 2 with optimised specimen design

Aim of Batch 2

- Creating of new datum line with optimised specimen design
- Comparison of different specimen designs
- Producing and testing of key anomalies

Turning in Titanium: Overview Batch 2

Comparison of Datum Line Batch1 and Batch2
4-Point Bending, Room Temperature
Load: Stress Controled, Sinus Shaped



Conclusions

• As assumed the new datum line shows longer LCF life

➢ New specimen design is able to prevent crack initiation edges

• For the new specimen design valid cracks and edge cracks fit together

➢ All results are used to create the new datum line for batch2

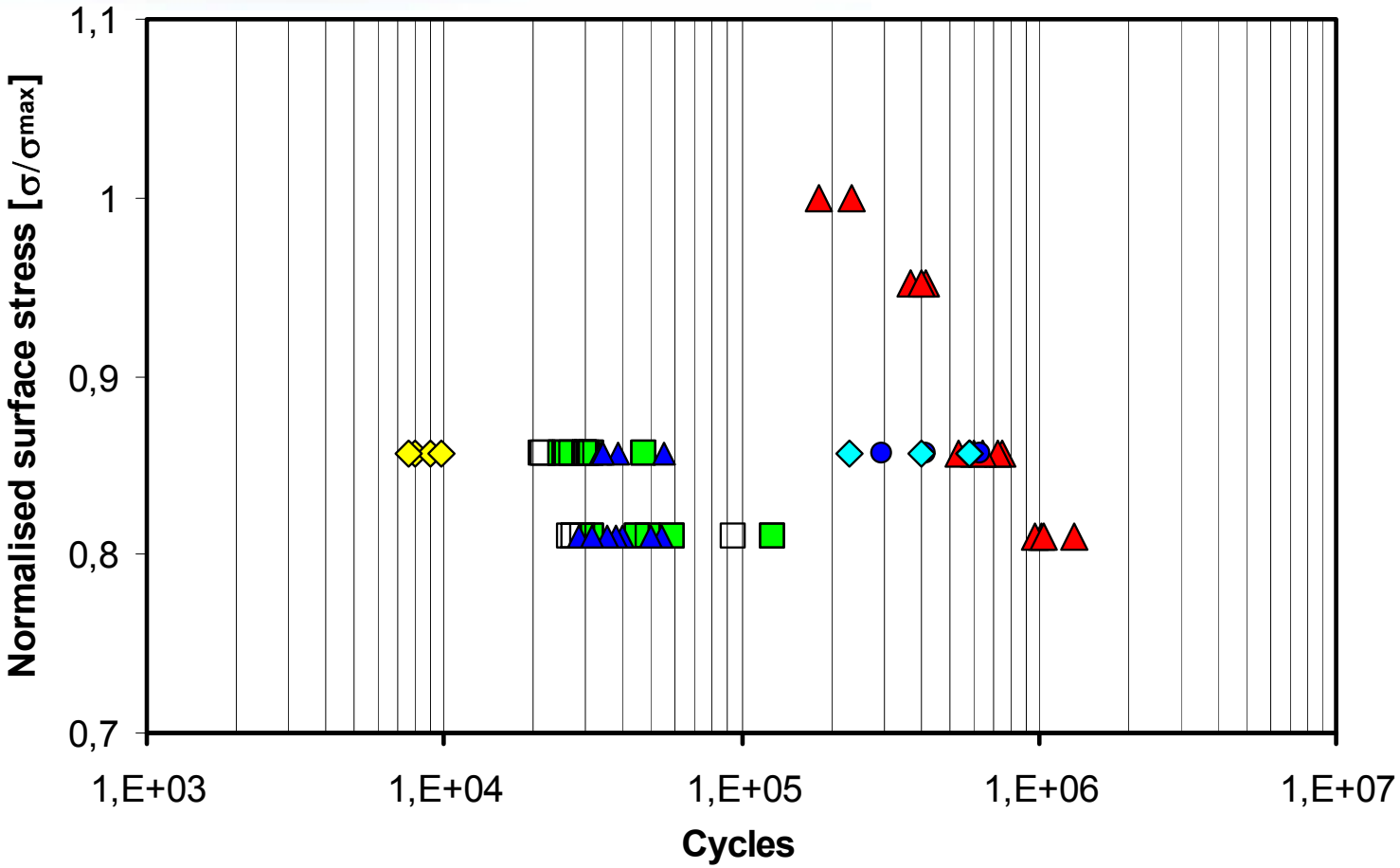
Key anomalies for batch 2

- Re-deposited parent material
- Heavy distortion due to contact with tool fixture during turning & rework
- Local microstructural deformation and adiabatic shear bands due to tool fracture

Turning in Titanium: Overview Batch 2

Overview

LCF Test on Batch 2 Specimens
4-Point Bending, Room Temperature
Load: Stress Controled, Sinus Shaped

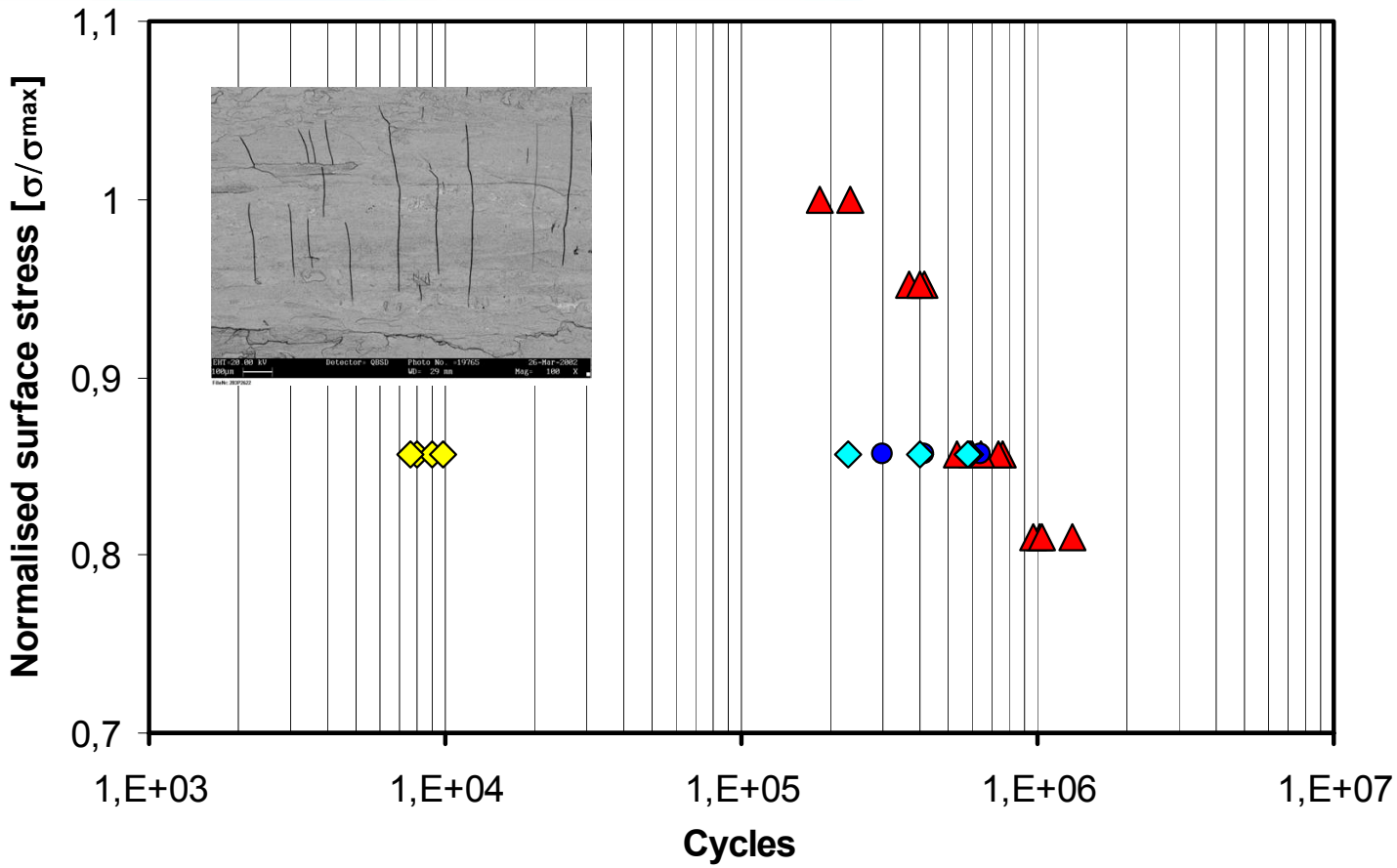


- MV03-V09 Datum Line
- fmV02V6 Heavly destored surface with individual EC indication
- fmV06V33 Heavly destored surface reworked
- fmV10V57 Heavly destored surface reworked
- fmV09V56 Adiabatic shear bands (from punching with pointless punch) valid
- fmV09V56 Adiabatic shear bands (from punching with pointless punch)
- fmV07V54 Re-deposited parent material

Turning in Titanium: Overview Batch 2

Heavily distortion

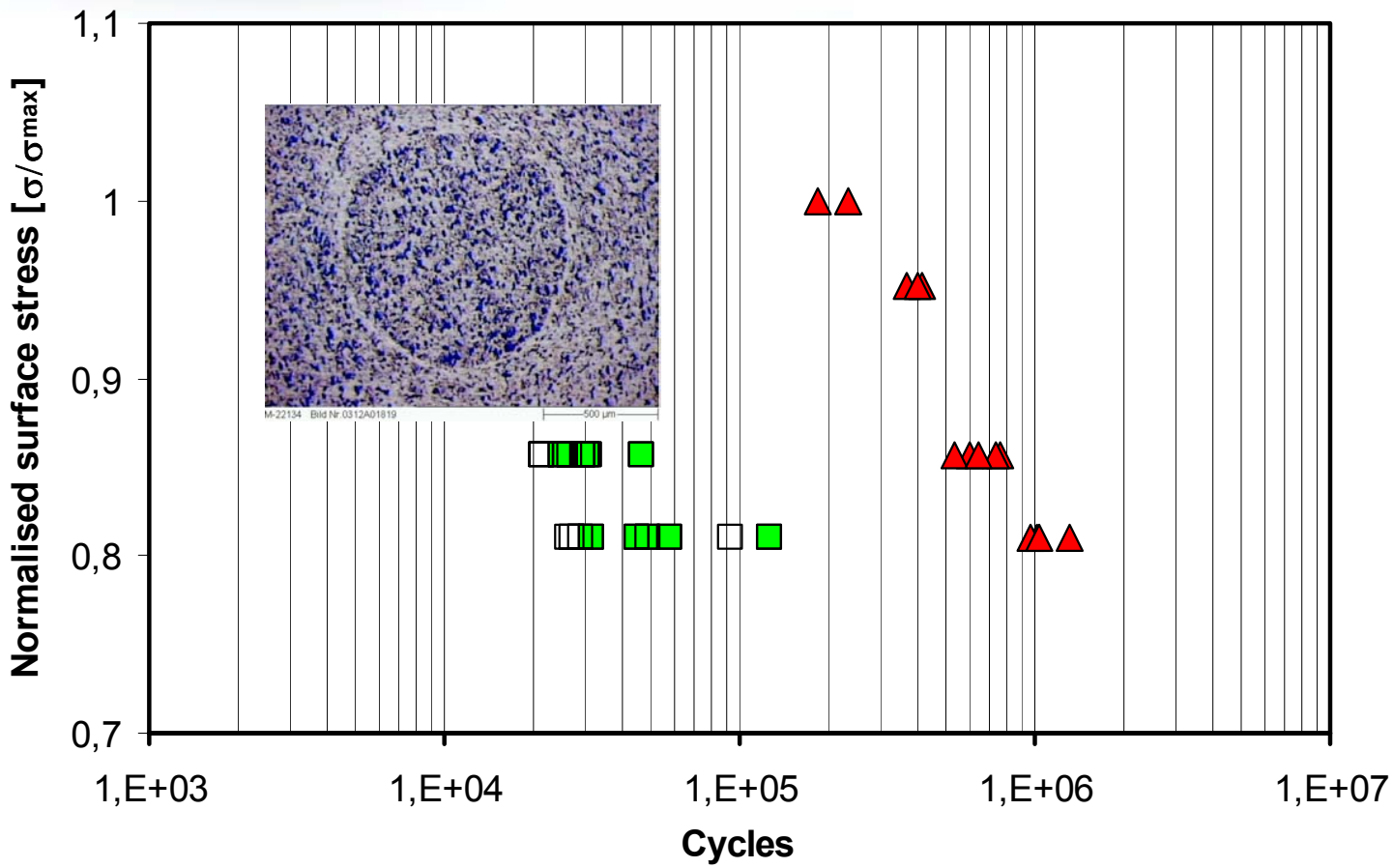
LCF Test on Batch 2 Specimens
4-Point Bending, Room Temperature
Load: Stress Controled, Sinus Shaped



Turning in Titanium: Overview Batch 2

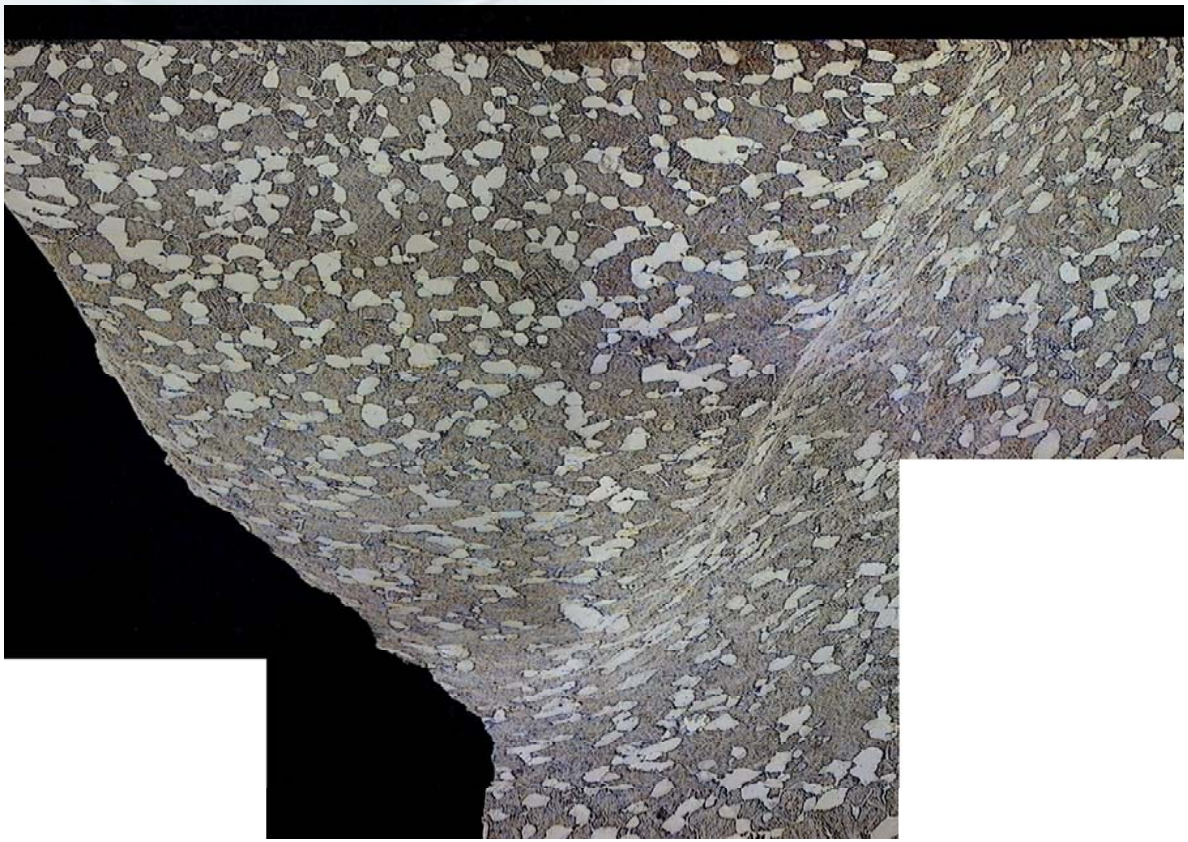
Adiabatic shear bands

LCF Test on Batch 2 Specimens
4-Point Bending, Room Temperature
Load: Stress Controled, Sinus Shaped

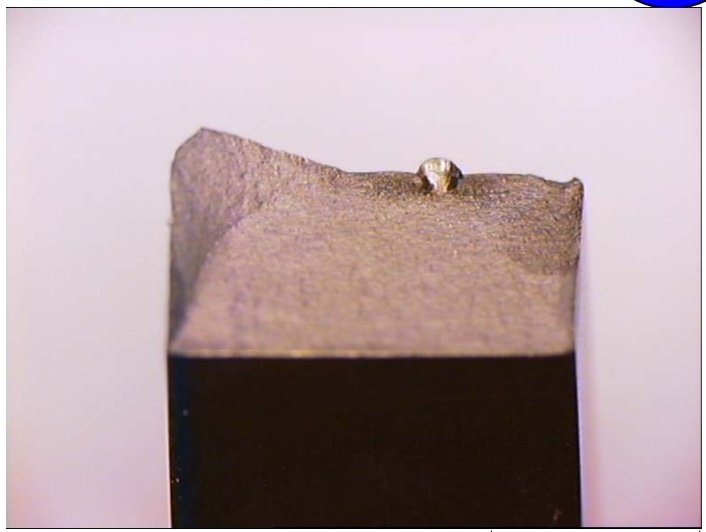


Turning in Titanium: Overview Batch 2

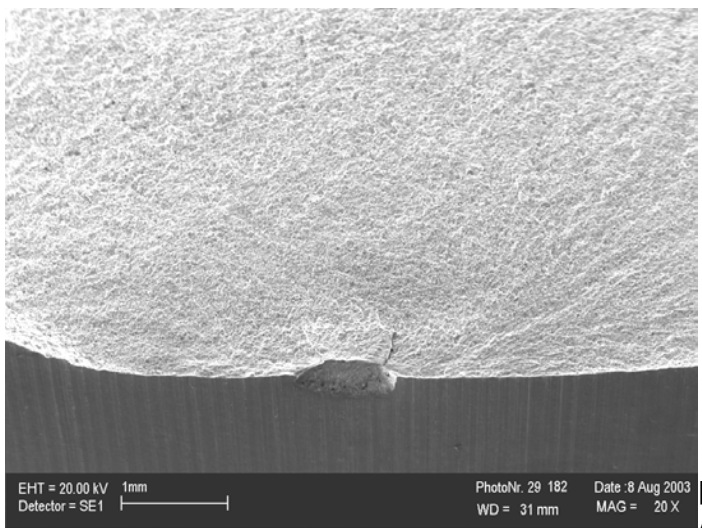
Adiabatic shear bands



M-22936 Bild Nr.0409A01395 200 µm

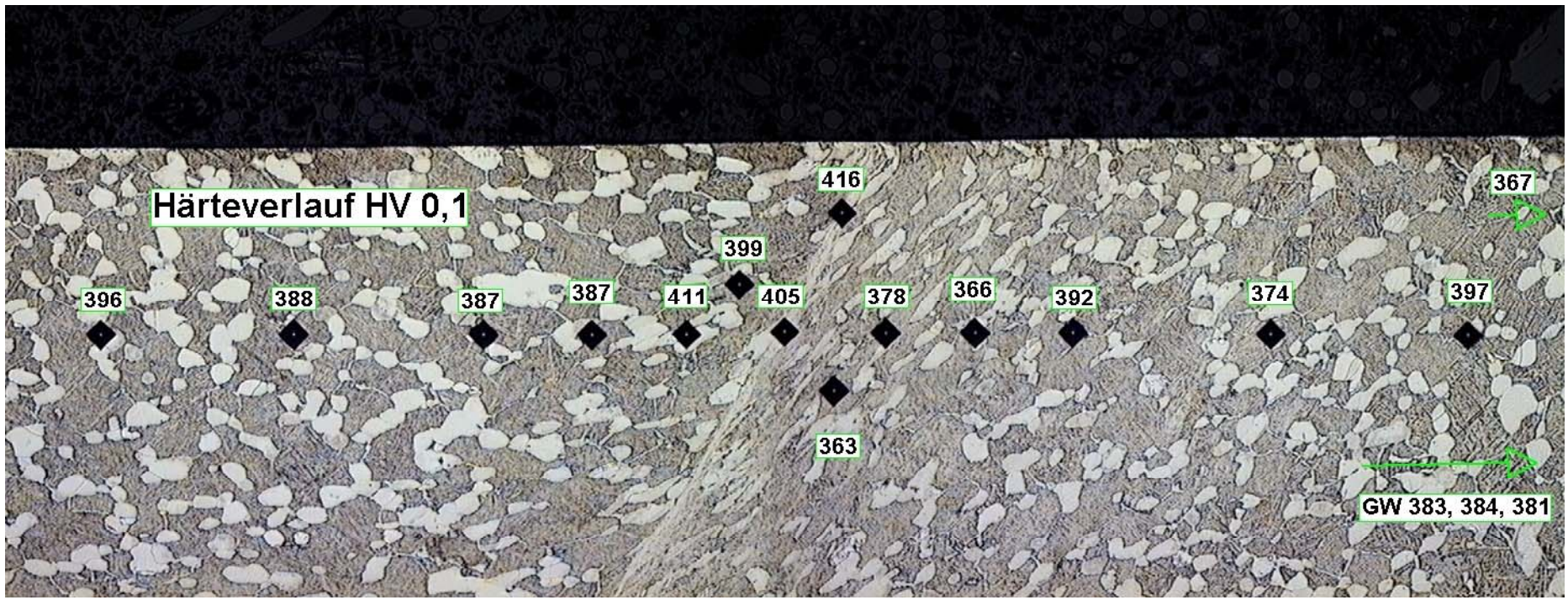


M-22936 Bild Nr.0409A01348 5 mm



R-14703 0308A00857

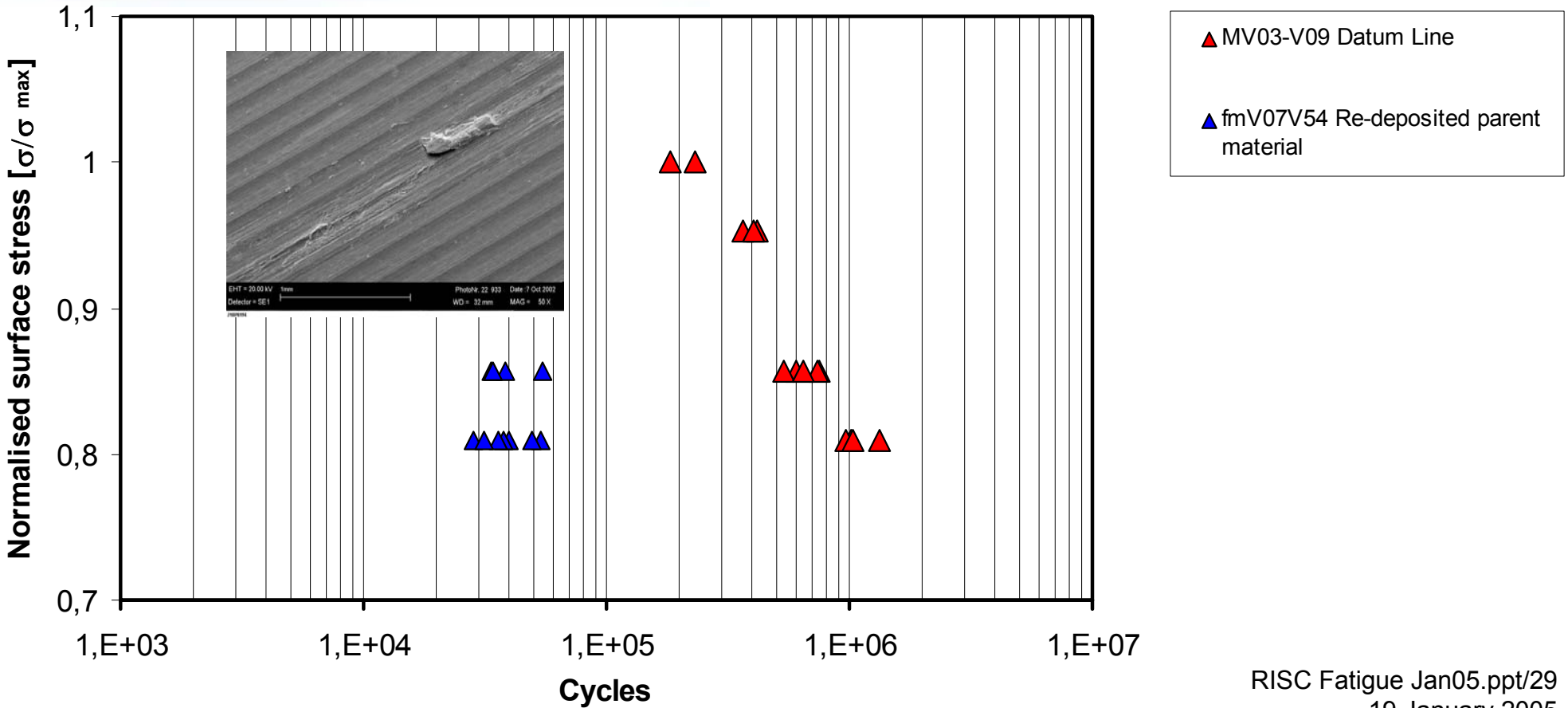
Adiabatic shear bands



Turning in Titanium: Overview Batch 2

Re-deposited parent material

LCF Test on Batch 2 Specimens
4-Point Bending, Room Temperature
Load: Stress Controled, Sinus Shaped



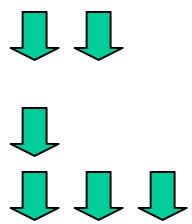
Conclusions

- Creating of new datum line with optimised specimen design
  - New specimen design able to prevent crack initiation from the edge

- Comparison of different specimen designs (same anomaly typ)
  - tbd

- Producing and testing of key anomalies
  - specimens of all key anomalies tested
    57 samples

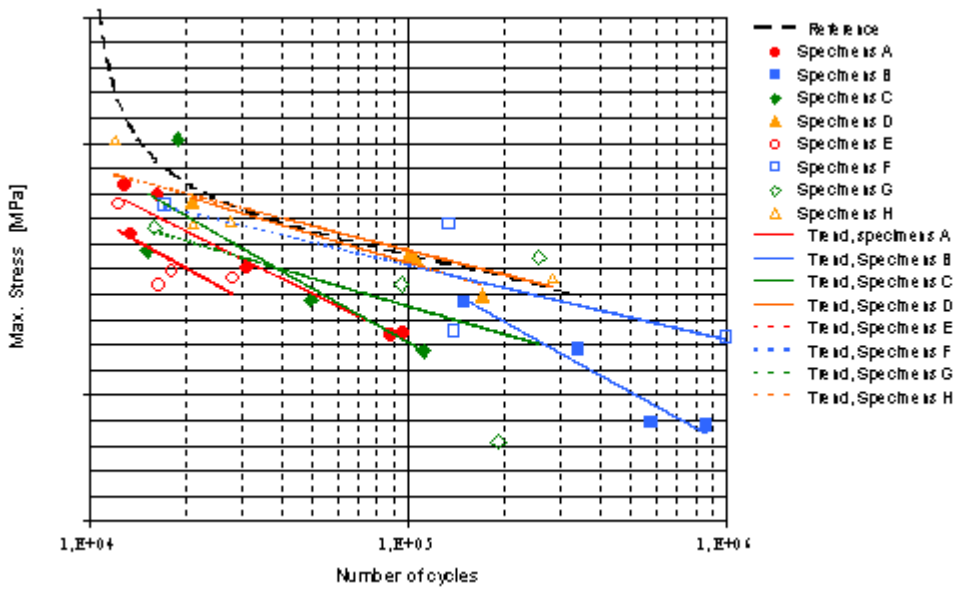
  - adiabatic shear bands
    (from punch with pointless tool)
  - Heavily distorted surface (reworked)
  - Re-deposit parent material



Turning in Inco 718

- Parameters examined
  - Depths of amorphous layer and distortion lower than in drilled holes

Parameter	Insert Wear	Distorted Layer Thickness (µm)	Amorphous Layer Thickness (µm)
A	New	8	2-4, discontinuous
B	New	6	2, discontinuous
C	New	15-20	2-4, discontinuous
D	New		2, discontinuous
E	Worn	8	Traces
F	Worn	4	Traces
G	Worn	15-20	No
H	Worn	10-15	Traces
Batch 1 Fatigue specimen machining matrix and anomalies produced.			

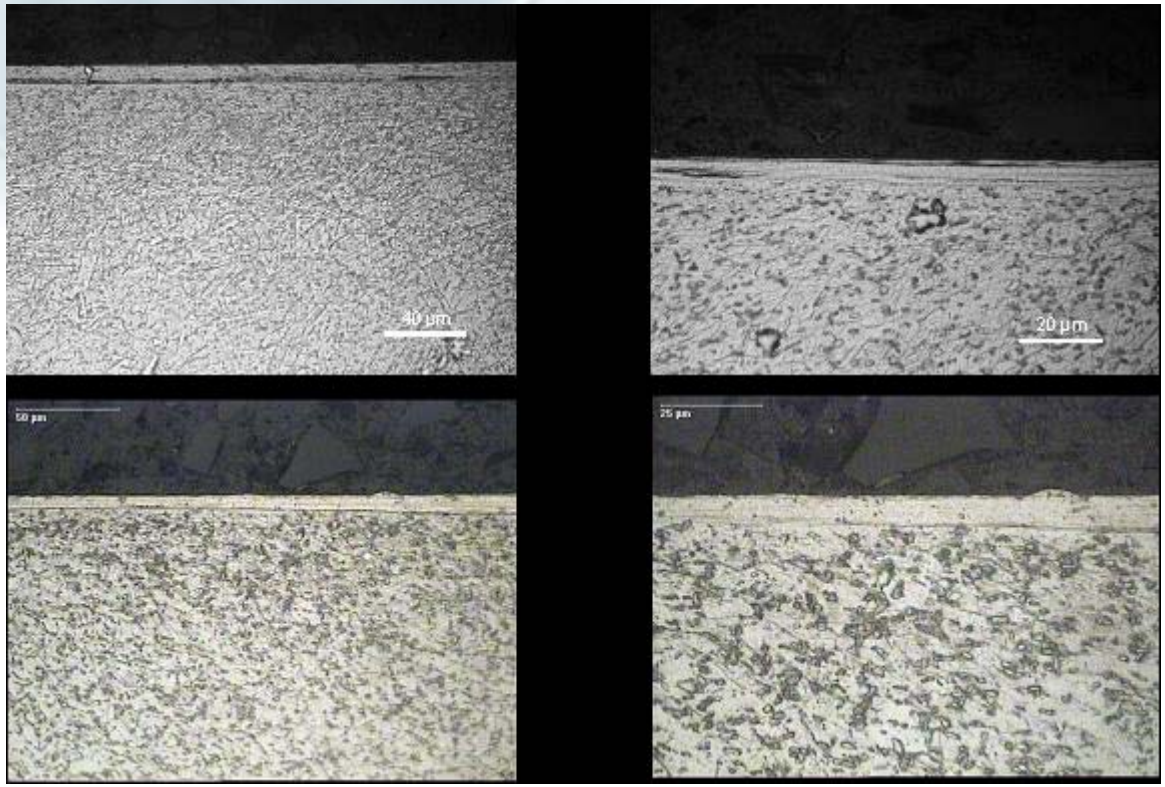


- Generally fatigue results don't show same deficit as in other features
- May be result of limited depths of damaged material

Conclusions from Batch 1 testing turned Inco 718

- Turning conditions applied to manufacturing of Batch 1 fatigue test specimens did not produce surface anomalies that gave a significant fatigue debit compared to the standard machining condition.
- Batch 2 fatigue test specimens will be manufactured using severe machining conditions, well beyond the industrial practice, in order to produce significant anomalies

Plans for Batch 2 turned Inco 718



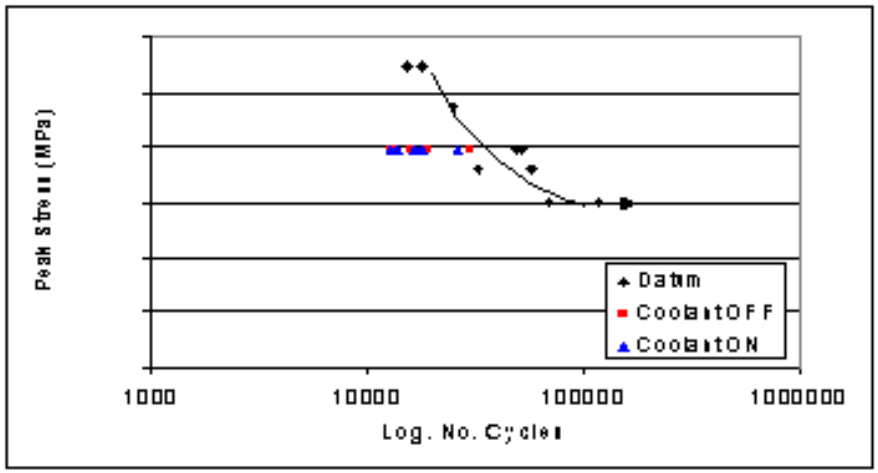
Metallographic sections showing amorphous layers produced in the preliminary Batch 2 specimens.

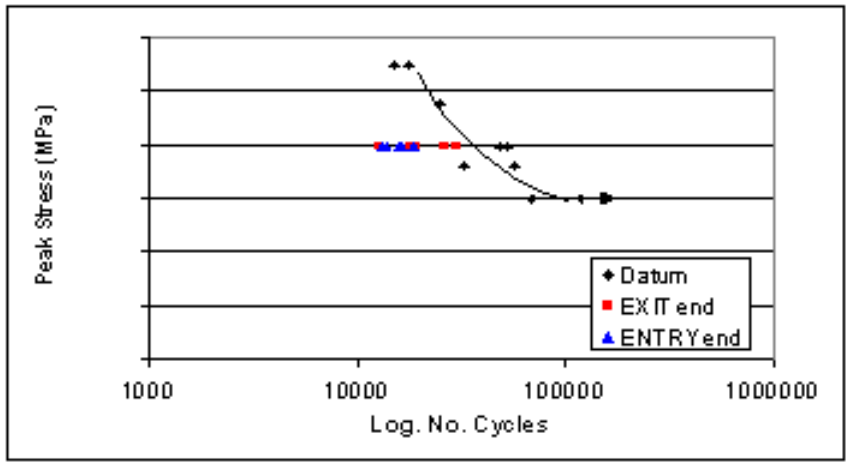
Parameter	Distorted Layer Thickness (µm)	Amorphous Layer Thickness (µm)
2A	10	1-3, discontinuous
2B	60	1-14, discontinuous
2C	80	1-14, discontinuous
2D	50	1-6, discontinuous
2E	60	1-6, discontinuous

Batch 2 Trial specimen machining matrix and anomalies produced.

- Matrix for batch 2

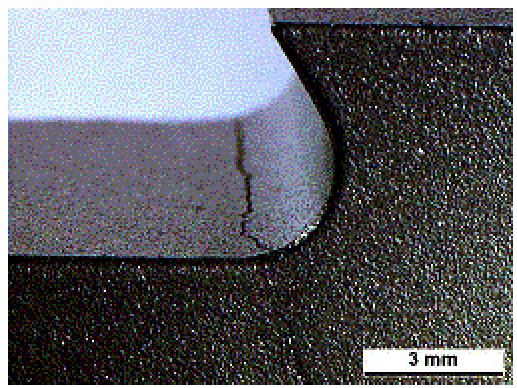
Broaching in Ti



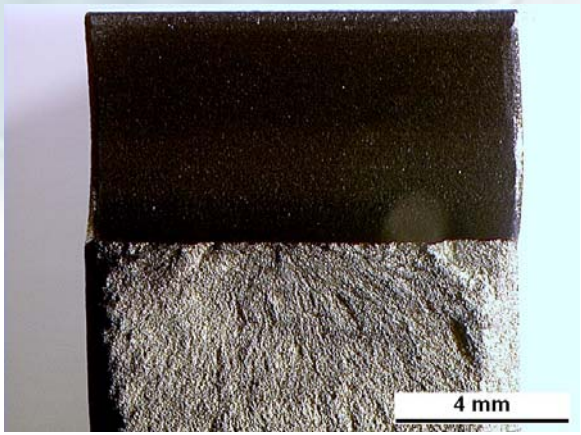


- Batch 1 results (partial) plotted as function of:-
  - Method of creation
  - Position

  At failure point
- Necessary to ensure anomaly is present in peak stress region to get relevant result
- Specimens represent “worn tool anomalies” and include smearing, scoring, chatter and exit burrs
- Specimens representing ”hard worn tool anomalies are in test

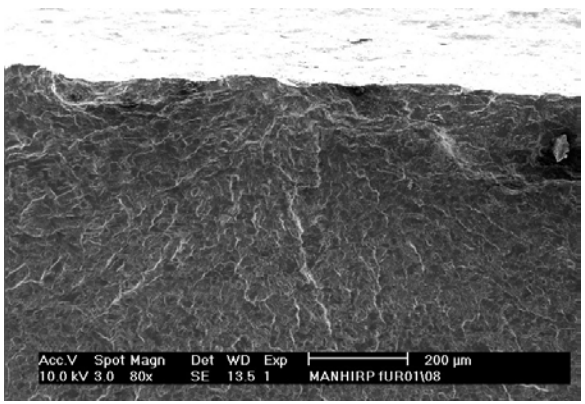


Examination of broached specimens



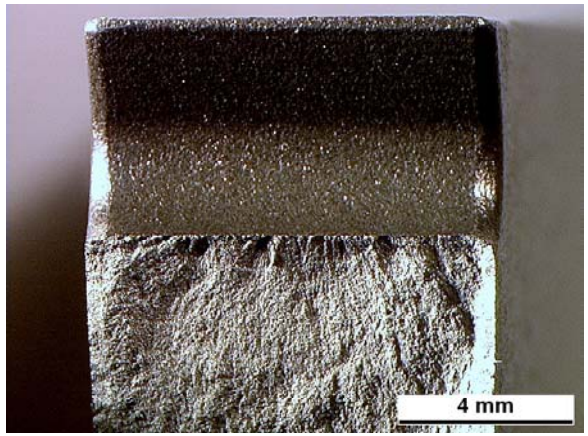
Photograph of the fatigue crack origin of a datum test-piece.

The origin is apparently from a single point.



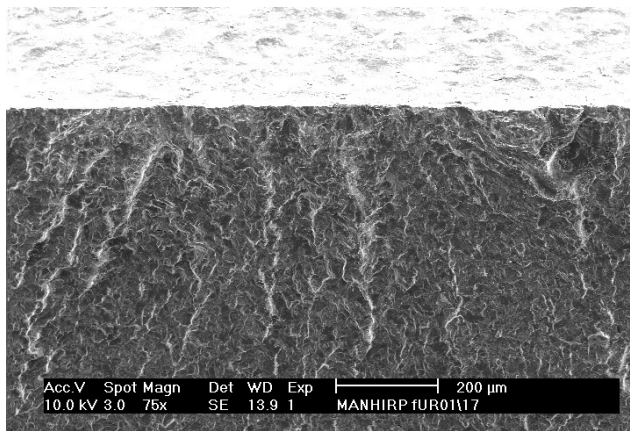
Photograph of the fatigue crack origin of one of the first ten specimens of the “worn tool anomaly”.

The origin of the fatigue crack appears to originate from a line covering approximately 5mm of the specimen width.



SEM micrograph of the fatigue crack origin of one of the first ten specimens of the “worn tool anomaly”.

No singular origin point is apparent.



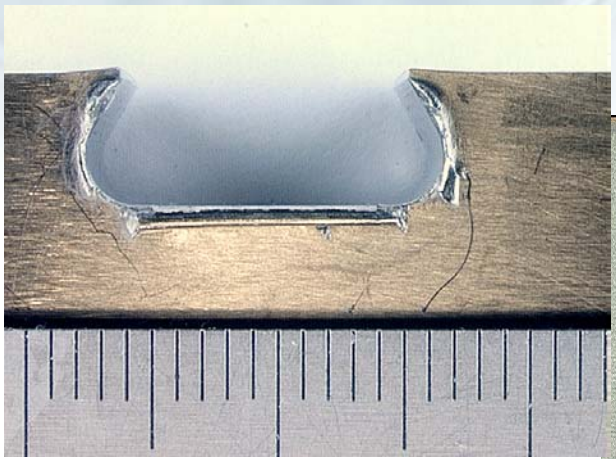
Completion of batch 1

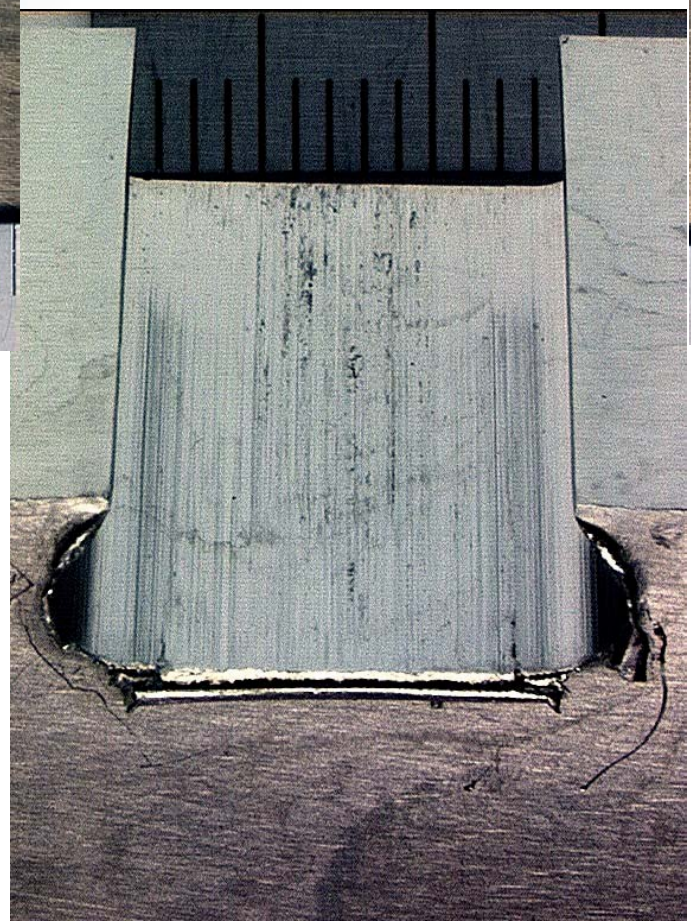
No. of Specimens	Type	Observed Anomalies	Current Progress
5	"Hard worn tool, same material smearing"		Examination
5	"Hard worn tool, foreign material smeared"		Examination
5	"Hard worn tool, no coolant, increased speed"		Examination
5	"Hard worn tool, chipped tooth"		Examination

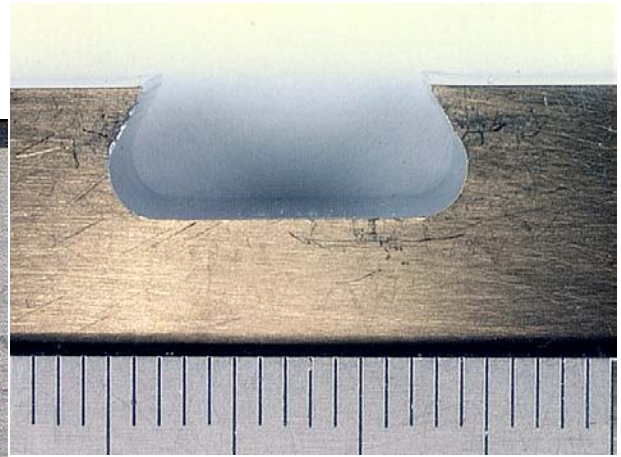
Batch 1 Fatigue specimen matrix and current status.

- Completion of batch 1 specimens

“Extreme Anomaly”







All “EXTREME” Type

Entry Indentation

Exit Deformation

Ti 6-4 Smearing

Exit Steps/Entry steps

Lines of Undulations

Chatter

Some “EXTREME” Type

Broach Slot Cracking

Severe Scoring

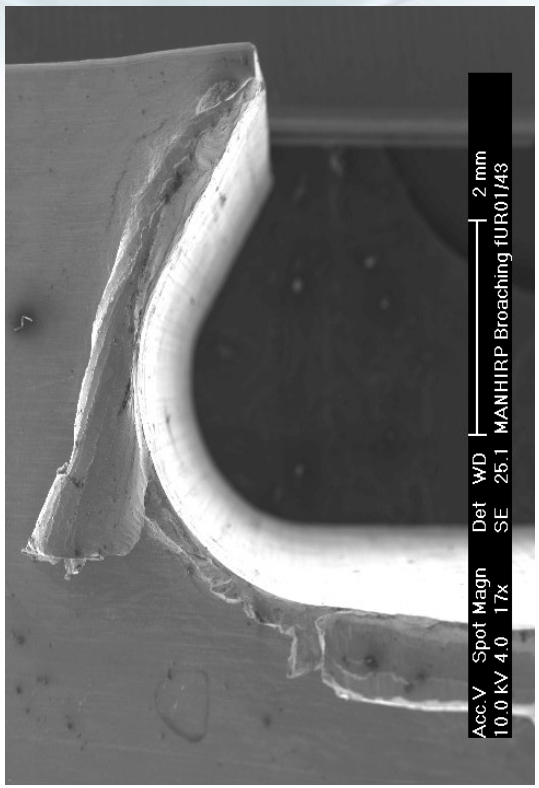
Score Folding/Cracking

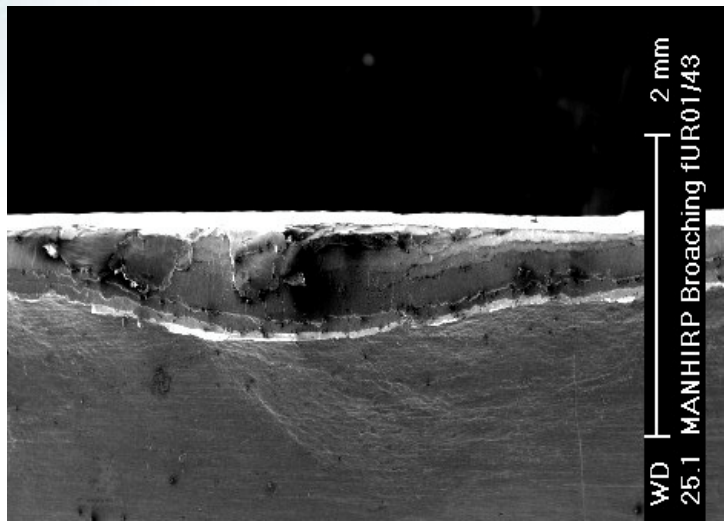
Exit Deformation Cracking

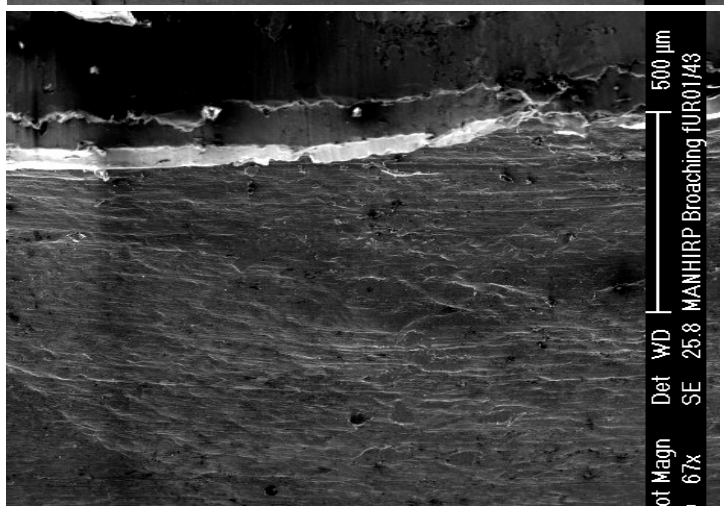
IN718 Smearing

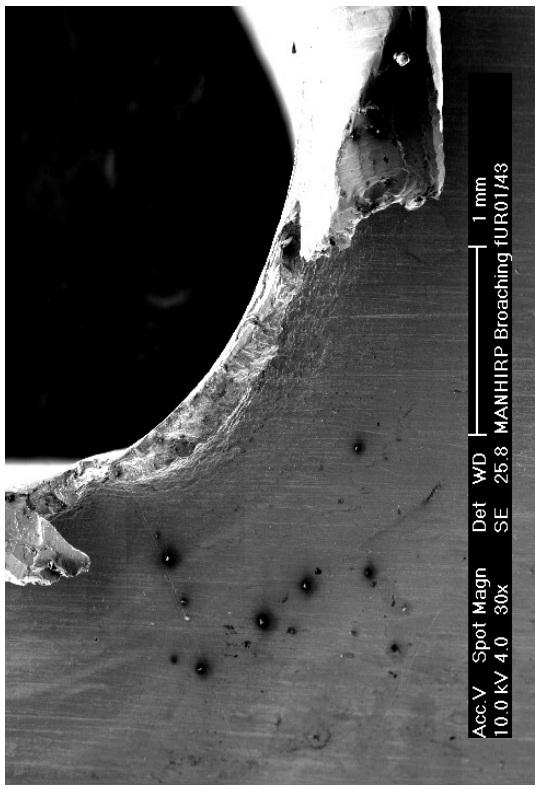
Plucking

Exit Deformation – In General

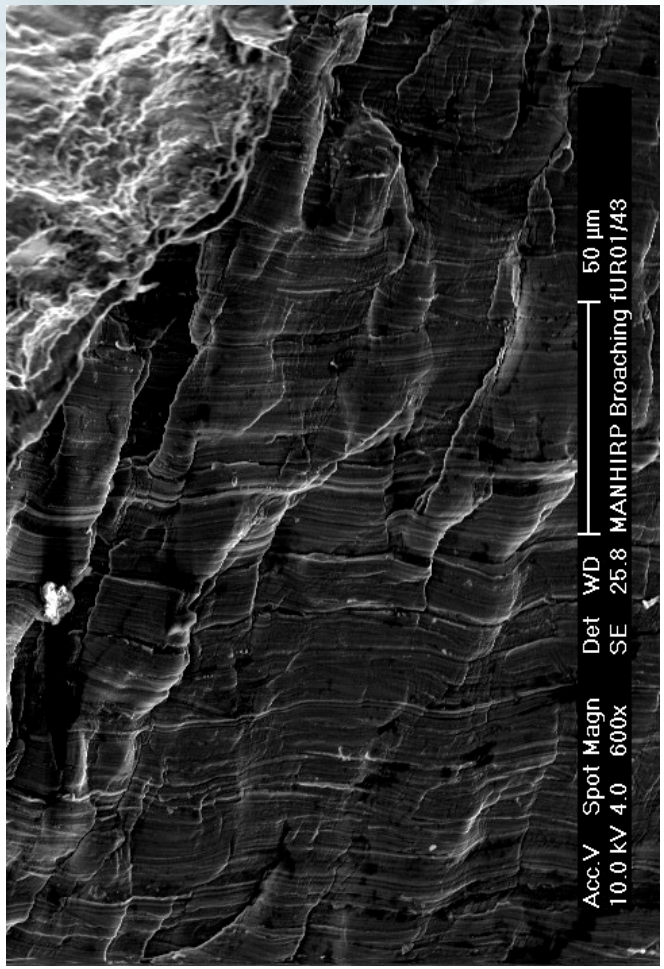


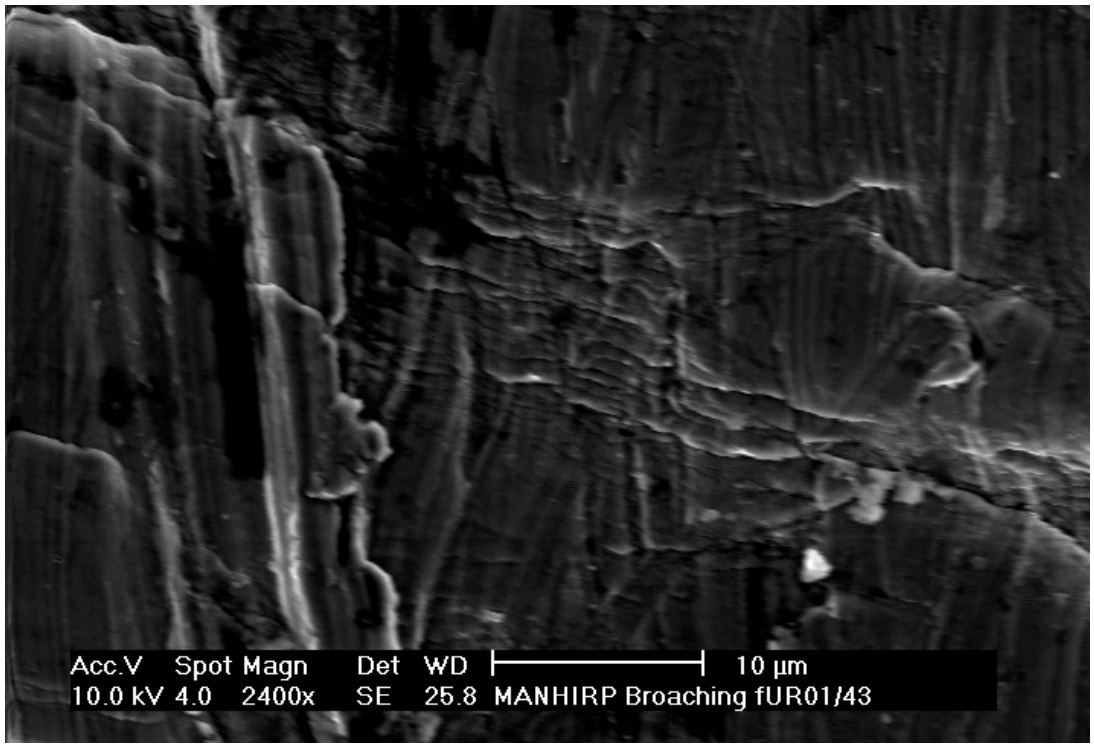






Exit Deformation – In General

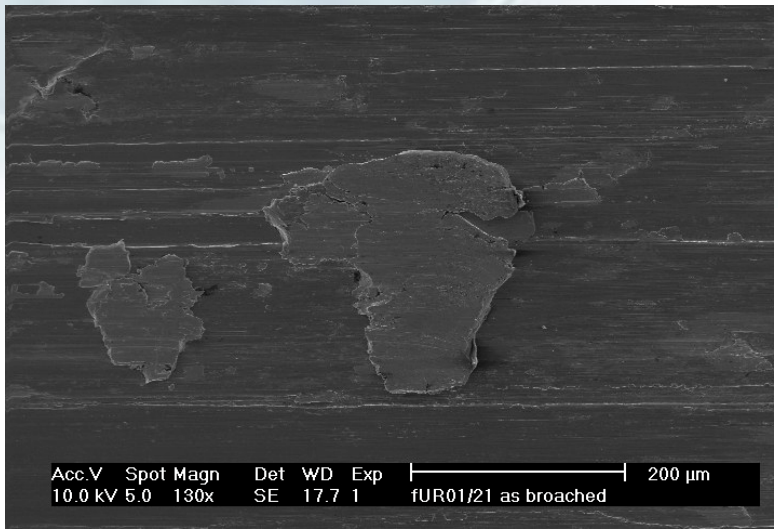


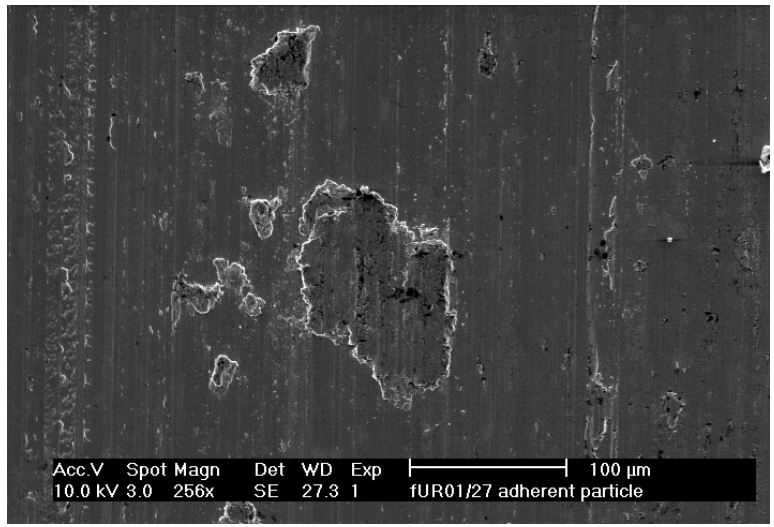


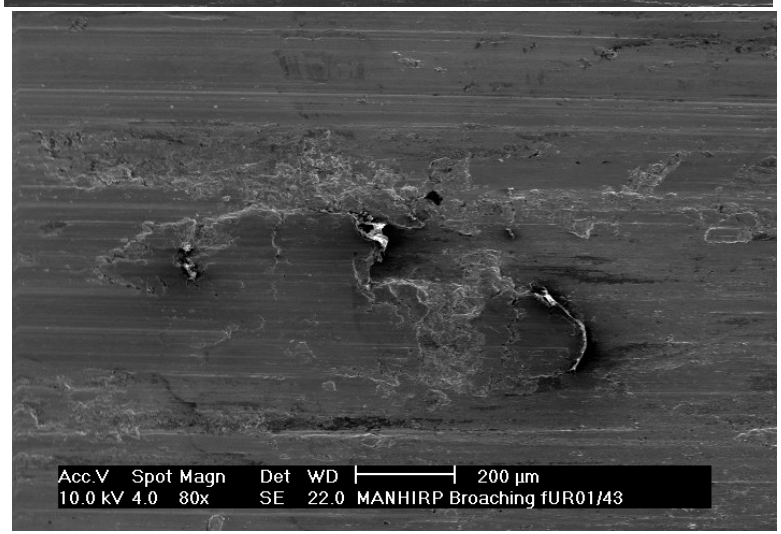
severe deformation = severe fatigue deficit

(at key position)

All “Extreme Anomaly” - Adherent Particles



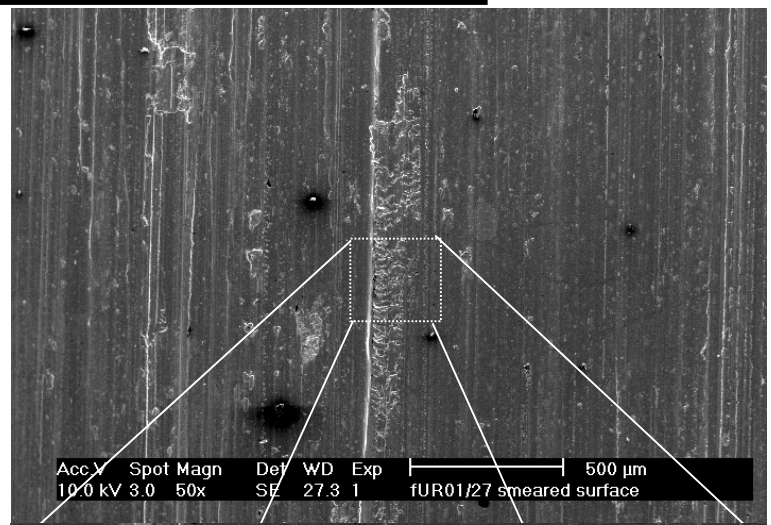


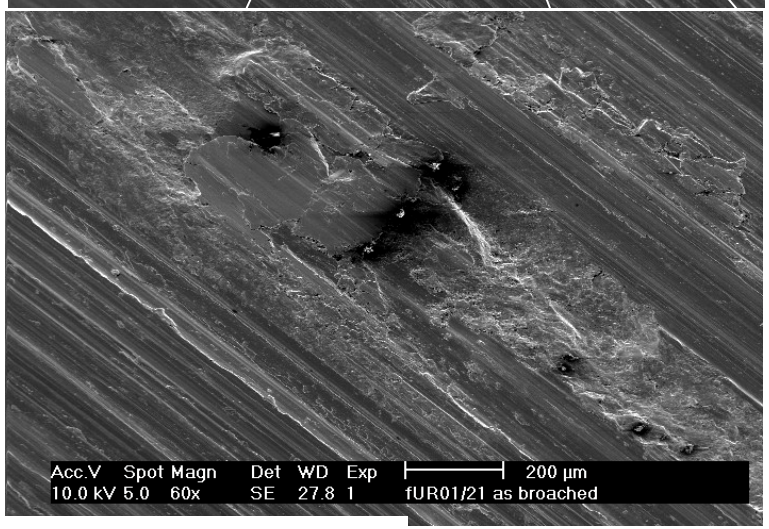


These were present on the test-pieces already tested and so, in themselves, may not represent a severe fatigue deficit – but in the non-peened condition they may be more significant (only if they coincide with the major stress location.

All “Extreme Anomaly” - Smeared Material/Disrupted Surface

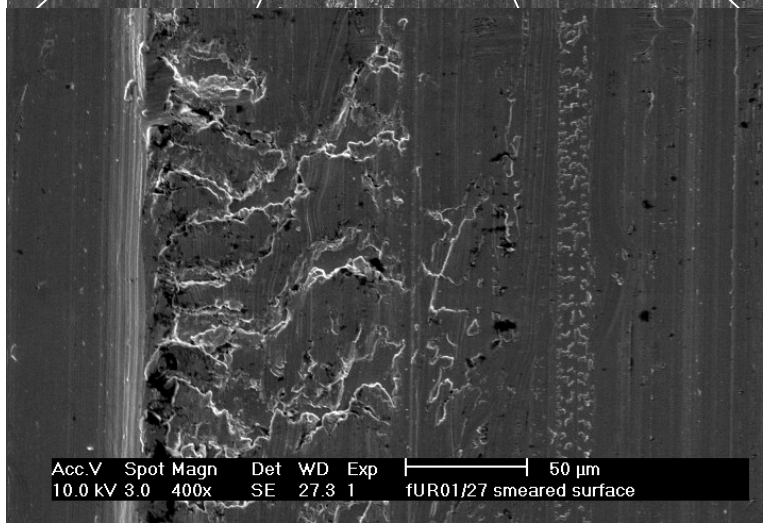
Severity of fatigue deficit will depend on location (very few found at the key stress position).



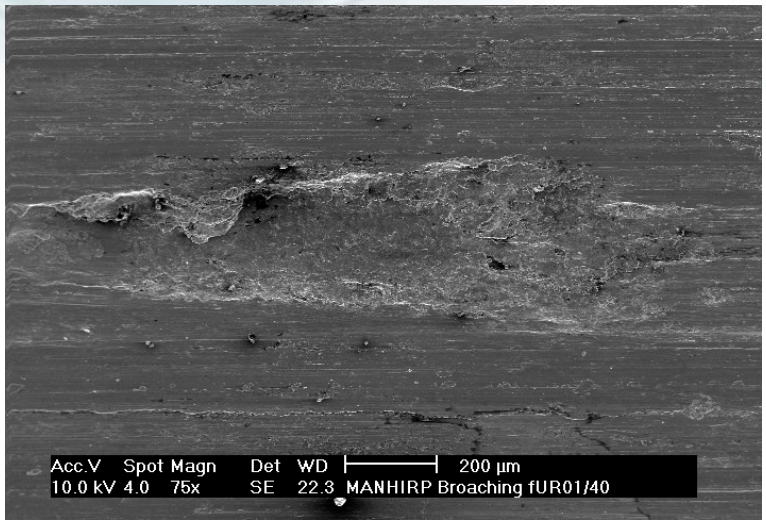


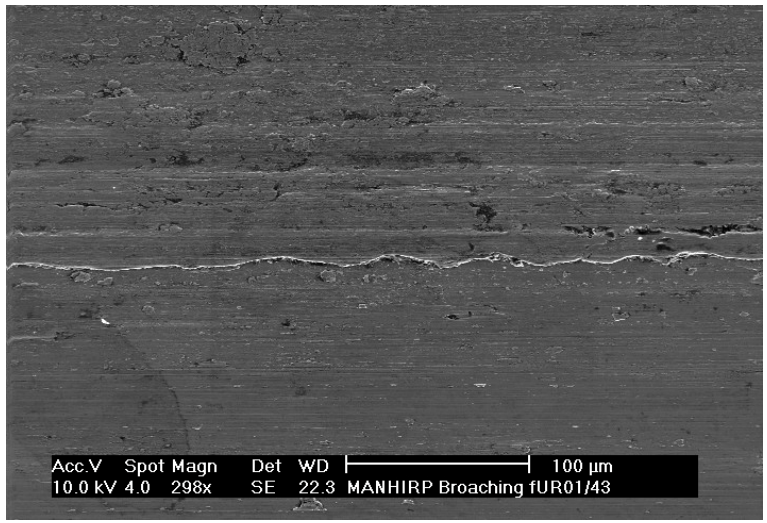
Isolated

Linear



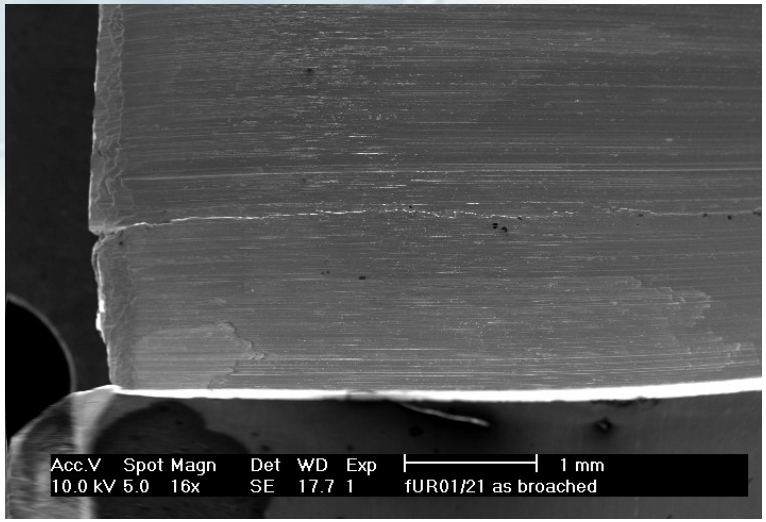
Some “Extreme Anomaly” - Plucking and Score Folding

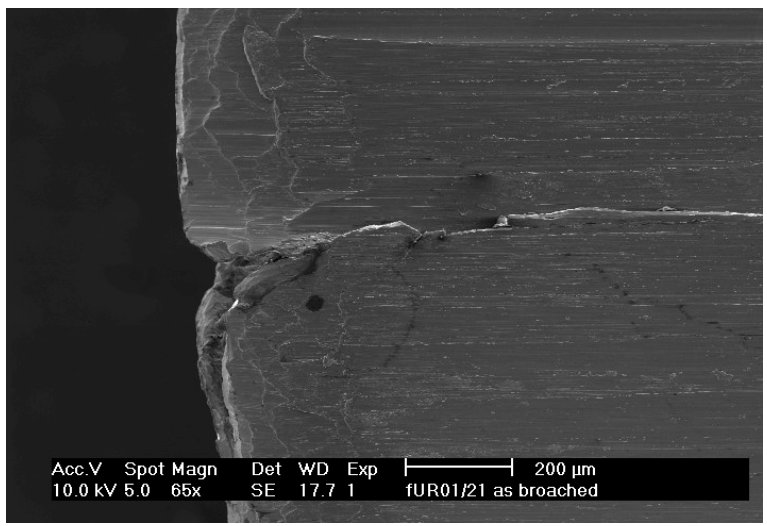


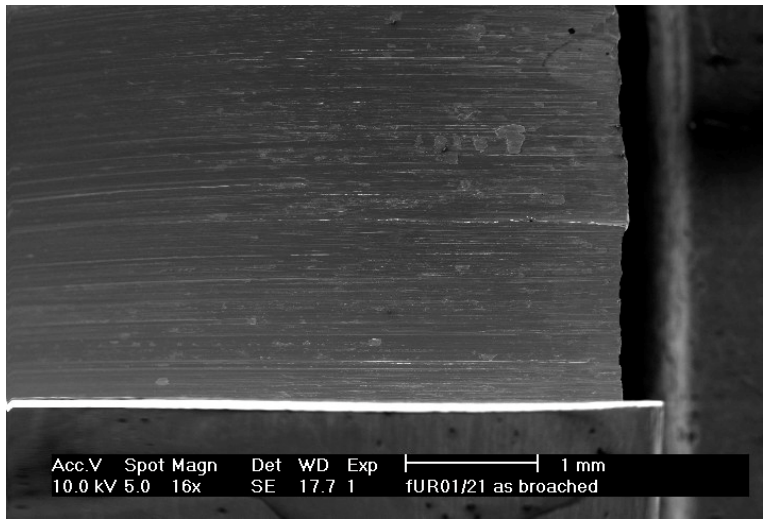


Either of these should represent some fatigue deficit if they occur at a peak stress position.

All “Extreme Anomaly” - Exit and Entry Steps





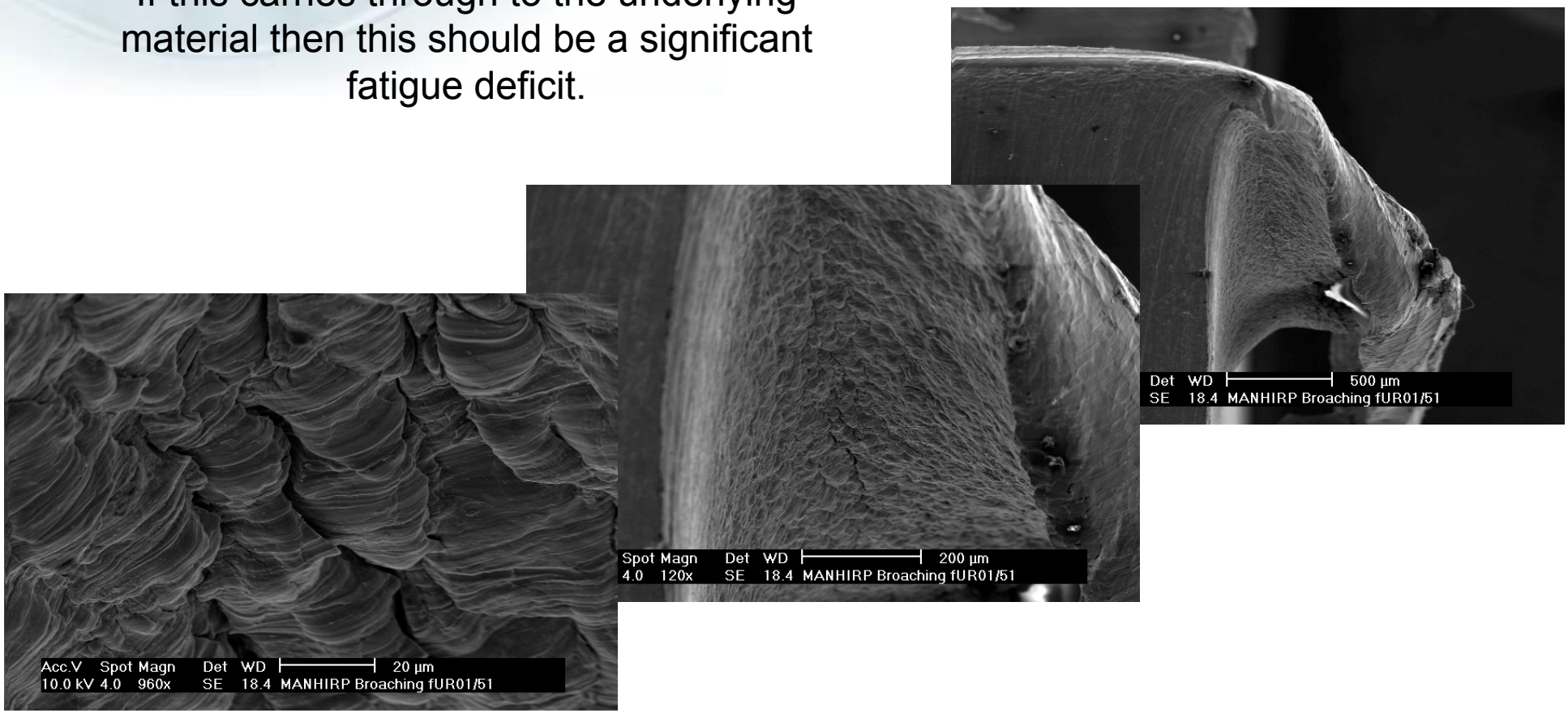


Entry Step – Geometric

Exit Step – Geometric and Smearing

All (?) “Extreme Anomaly” - Exit Deformation Cracking

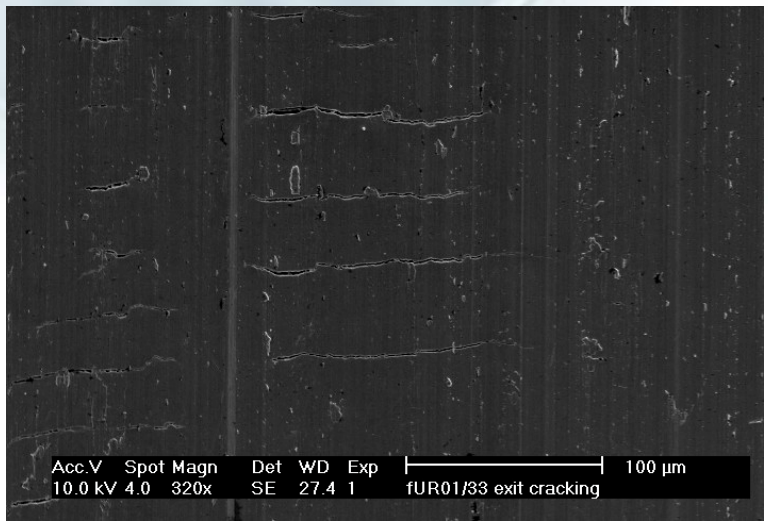
If this carries through to the underlying material then this should be a significant fatigue deficit.

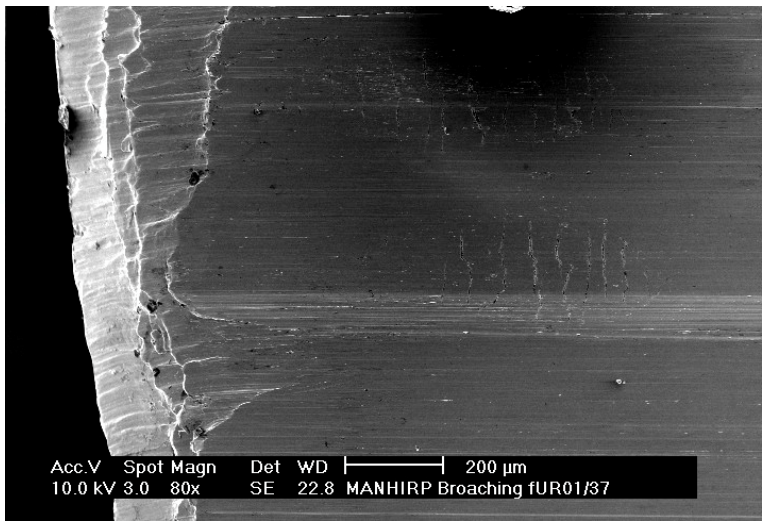


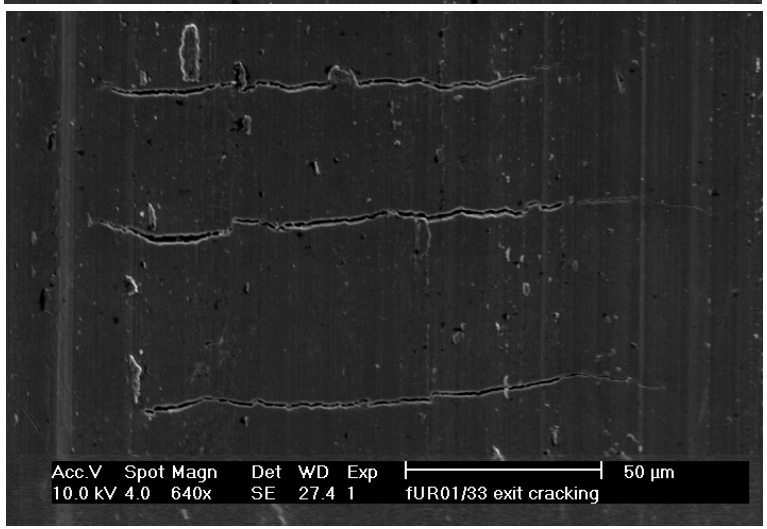
"Extreme Anomaly"

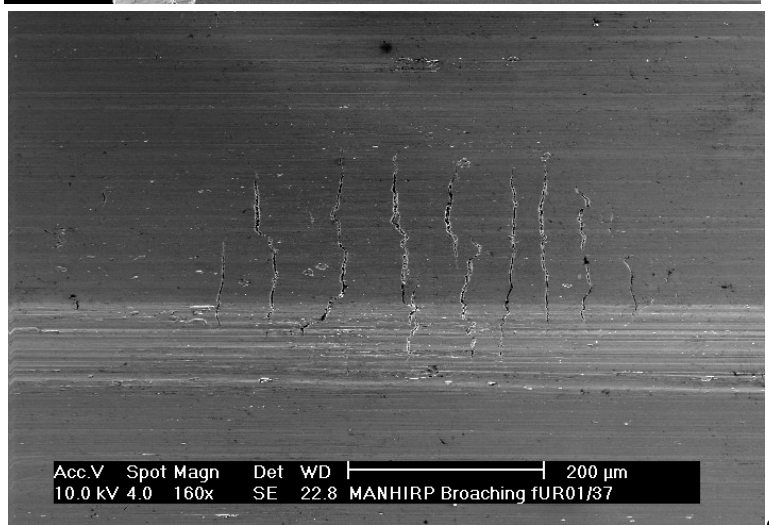
No.	"EXTREME ANOMALY" Type	Current Progress
5	"SAME MATERIAL SMEARING" Hard Worn Tool No Coolant	NDE/Fatigue
5	"FOREIGN MATERIAL SMEARING" Hard Worn Tool No Coolant	NDE/Fatigue
5	**"OVERHEATING"** **Hard Worn Tool** **Increased Speed** **No Coolant**	**NDE/Fatigue**
5	"HEAVY SCORING" Hard Worn Tool Chipped Tooth	NDE/Fatigue

Overheating Type - Broach Slot Cracking







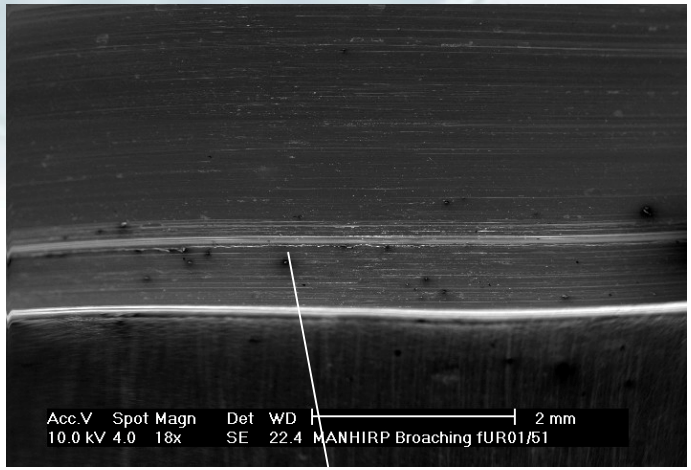


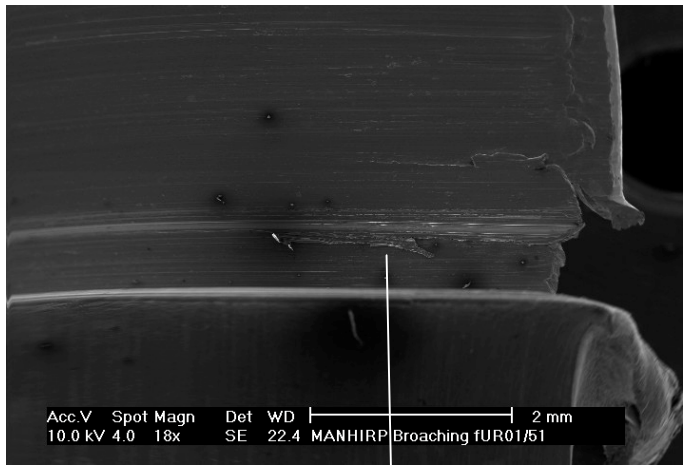
Should represent severe deformation or overheating and therefore severe fatigue deficit (irrespective of position?).

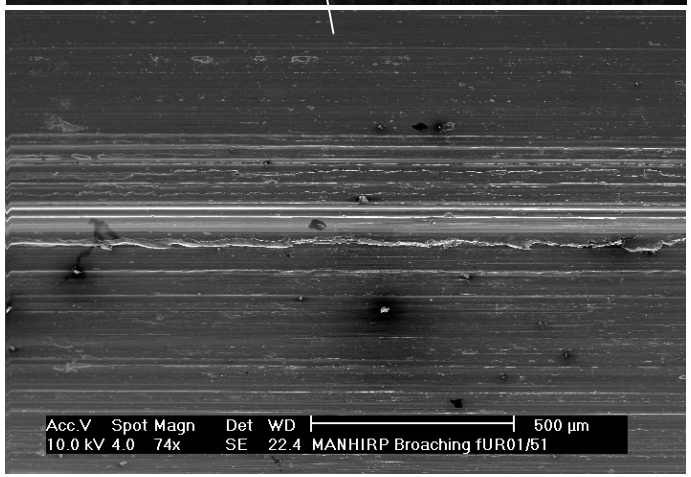
"Extreme Anomaly"

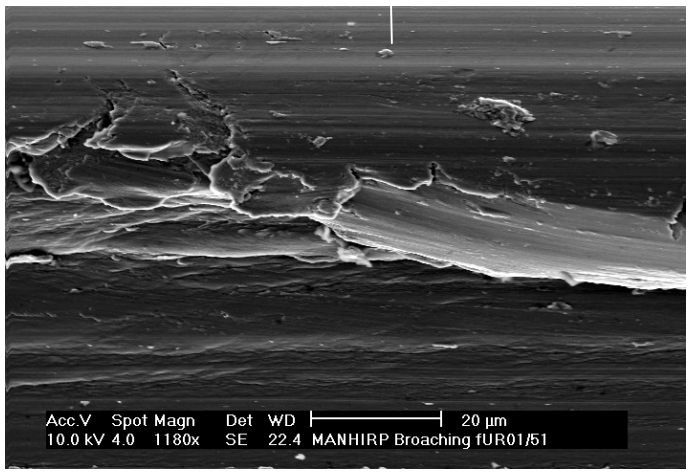
No.	"EXTREME ANOMALY" Type	Current Progress
5	"SAME MATERIAL SMEARING" Hard Worn Tool No Coolant	NDE/Fatigue
5	"FOREIGN MATERIAL SMEARING" Hard Worn Tool No Coolant	NDE/Fatigue
5	"OVERHEATING" Hard Worn Tool Increased Speed No Coolant	NDE/Fatigue
5	**"HEAVY SCORING"** **Hard Worn Tool** **Chipped Tooth**	**NDE/Fatigue**

Heavy Scoring Type - Score Folding/Cracking



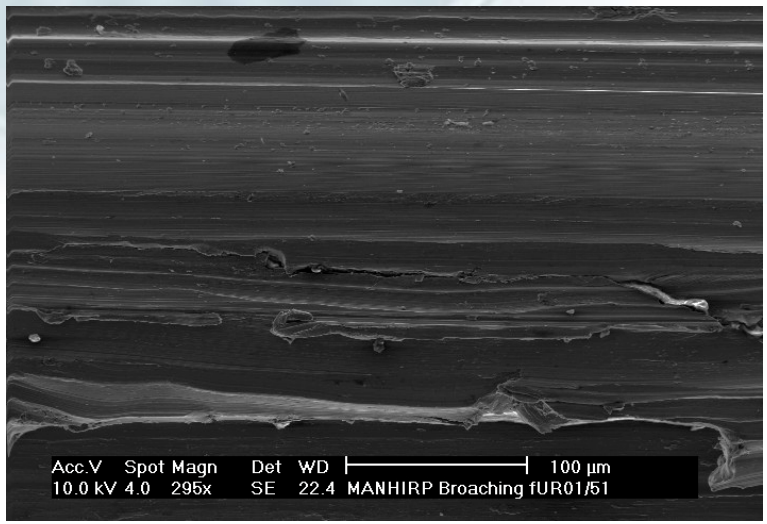


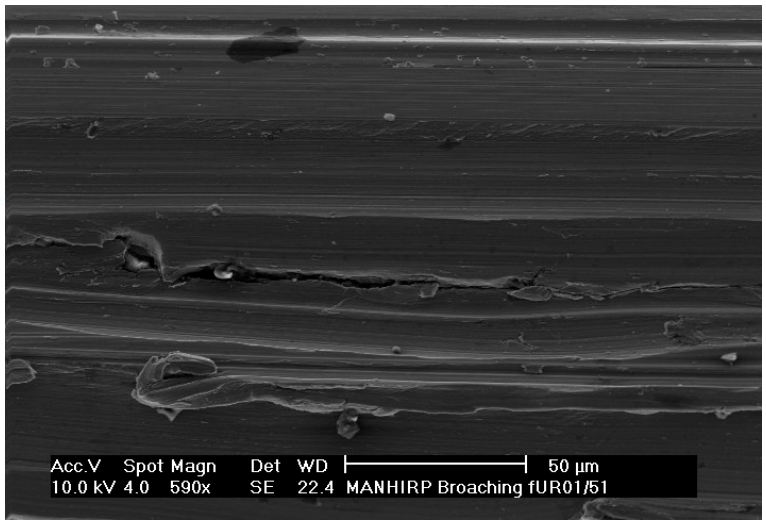


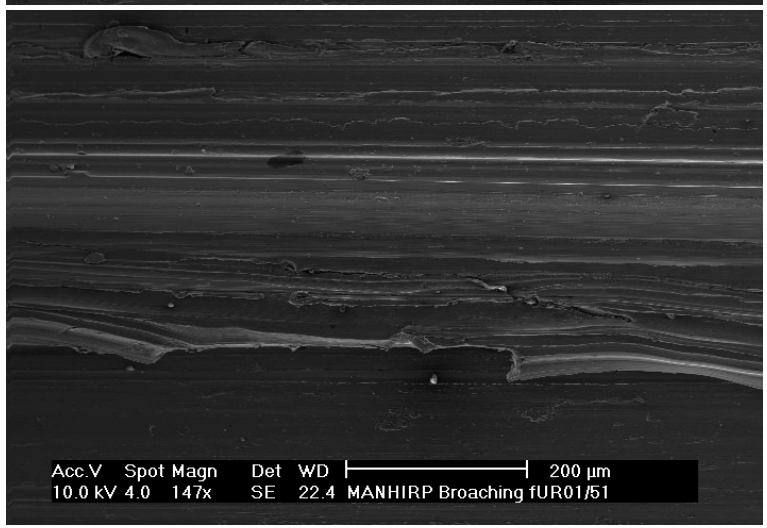


Because of its location should produce severe fatigue deficit, especially with cracking.

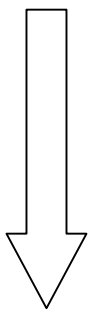
Score Folding/Cracking







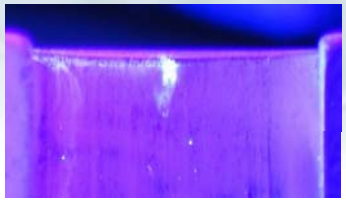
Cracking at key stress position will represent severe fatigue deficit.

Minor Anomalies		Smearing – smeared on material Smearing – disrupted surface Plucking Worked Surface undulations Chatter
Intermediate	Exit Deformation Occurs to some extent on all samples. Effect depends on severity	Entry step and deformation Exit step and deformation Scoring from chipped tooth
Severe Anomalies		Surface Cracking (Overheat) Exit deformation Exit deformation cracking Score deformation cracking

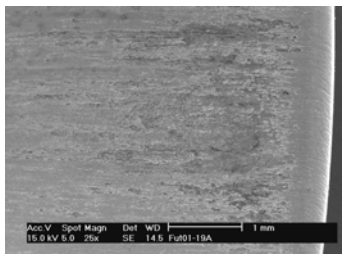
No.	Type	Progress to Date	To Do…
10	Datum	Fatigue tested, examined, fatigue origins examined	Complete
10	Worn Tool Anomaly	Fatigue tested, examined, surface visible anomaly mapped, fatigue origins examined.	Remaining sectioning to be completed.
10	Hard worn tool anomaly	Examined, surface visible anomaly mapped, NDE complete, in fatigue testing	Fatigue origins, section examination
5	Hard worn tool, same material smearing	examined, surface visible Anomaly Mapped	NDE, fatigue testing, fatigue origins, section examination
5	Hard worn tool, foreign material smeared	examined, surface visible anomaly mapped	NDE, fatigue testing, fatigue origins, section examination
5	Hard worn tool, no coolant, increased speed	examined, surface visible anomaly mapped	NDE, fatigue testing , fatigue origins, section examination
5	Hard worn tool, chipped tooth	examined, surface visible anomaly mapped	NDE, fatigue testing , fatigue origins, section examination
8	Datum – Not Peened		

Broaching in Inco 718

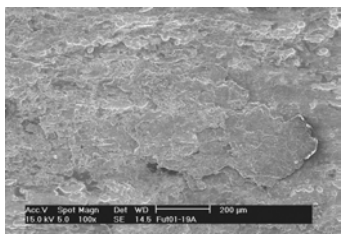
Optical image looking down on slot after macro etching.



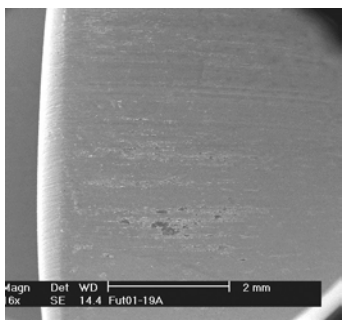
Optical image looking at the slot entrance during FPI.



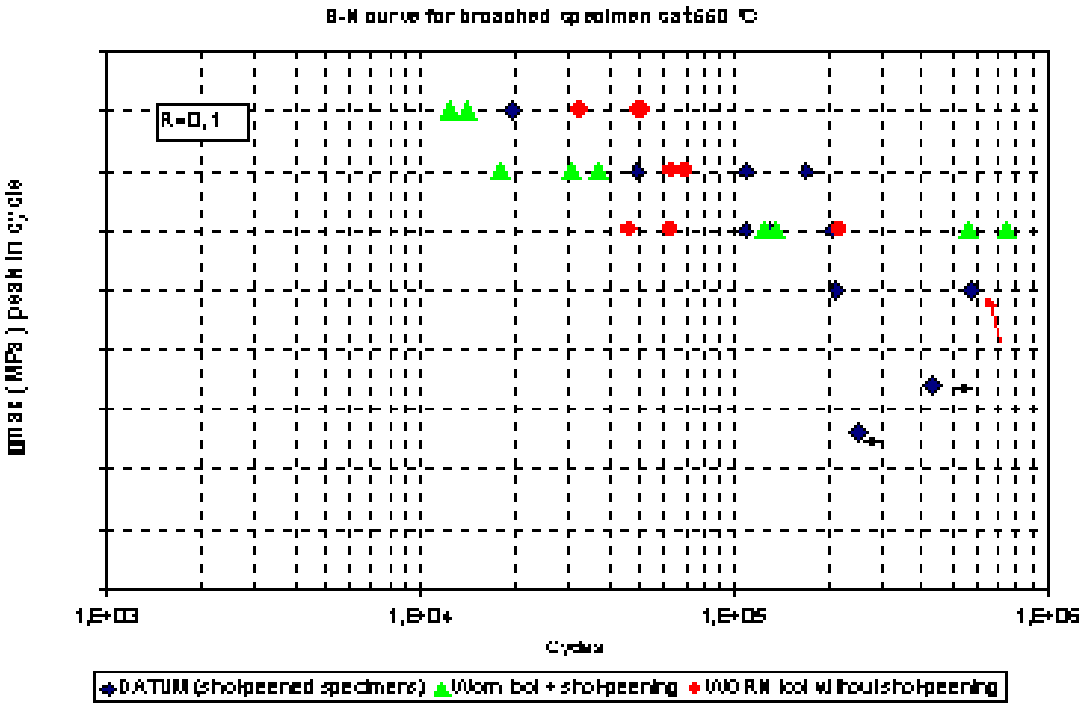
SEM image showing disrupted surface features at entry to slot.



Area of image above showing a close up of a smeared on particle.



SEM Image showing smeared on particle towards exit of specimen



- Difference between datum, worn tool with & without shot peening is not large
- Conclusions
  - more severe anomalies must be created
  - Position of anomalies is important

Conclusion on fatigue testing of broached specimens in Inco 718

- Fatigue initiation is related to micro structural features both in “non-damaged” and “damaged specimens”.
- It is damage just below the surface at slot root, which is influencing fatigue initiation. Damage on surface (smearing) is not affecting fatigue life.
- Microstructure (grains) is acting as initiators in “datum” and “damaged but non peened specimens”. Distorted layer in the latter is discontinuous and shallow in depth, and is not the weakest link in the volume of material subjected to maximum stress. Origin is shifted to grains located sub-surface.
- Damaged & peened specimens’ origins are always related to distorted layer or hard particles. Damage in material at that area, and perhaps a combination of mechanical & residual stresses seems to be “pushing” to failure starting there.
- Scatter in lives among the three conditions for the same stress level is between 1 and 6, which is not unusual. Trends are not clear, and might change if the number of test is increased.