
核二廠一號機反應爐支撐裙板受損錨定螺栓 熱室檢驗暨受損機制分析

核能研究所 張中興

民國 101 年 5 月 14 日

行政院原子能委員會

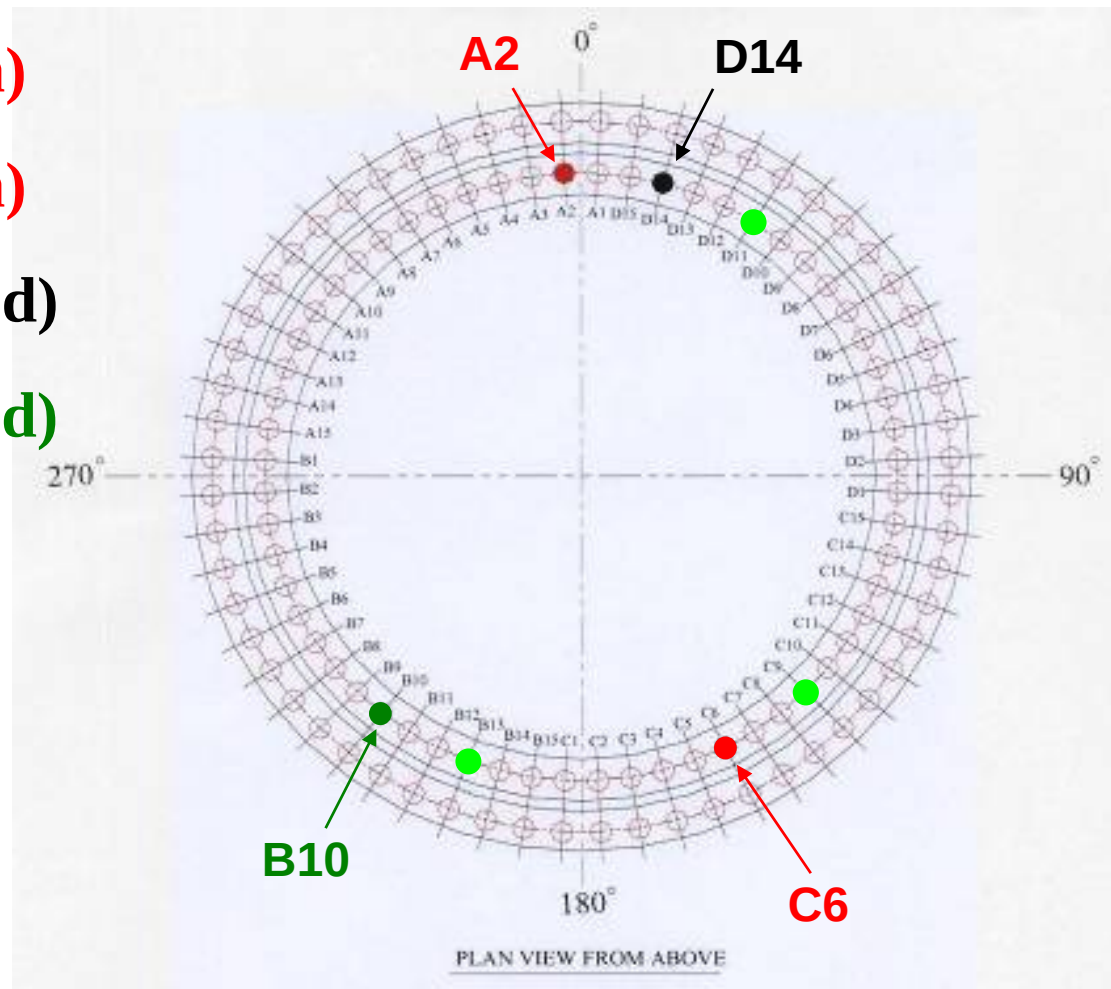
受損螺栓方位角

A2 斷裂(Broken)

C6 斷裂(Broken)

D14 龜裂(Cracked)

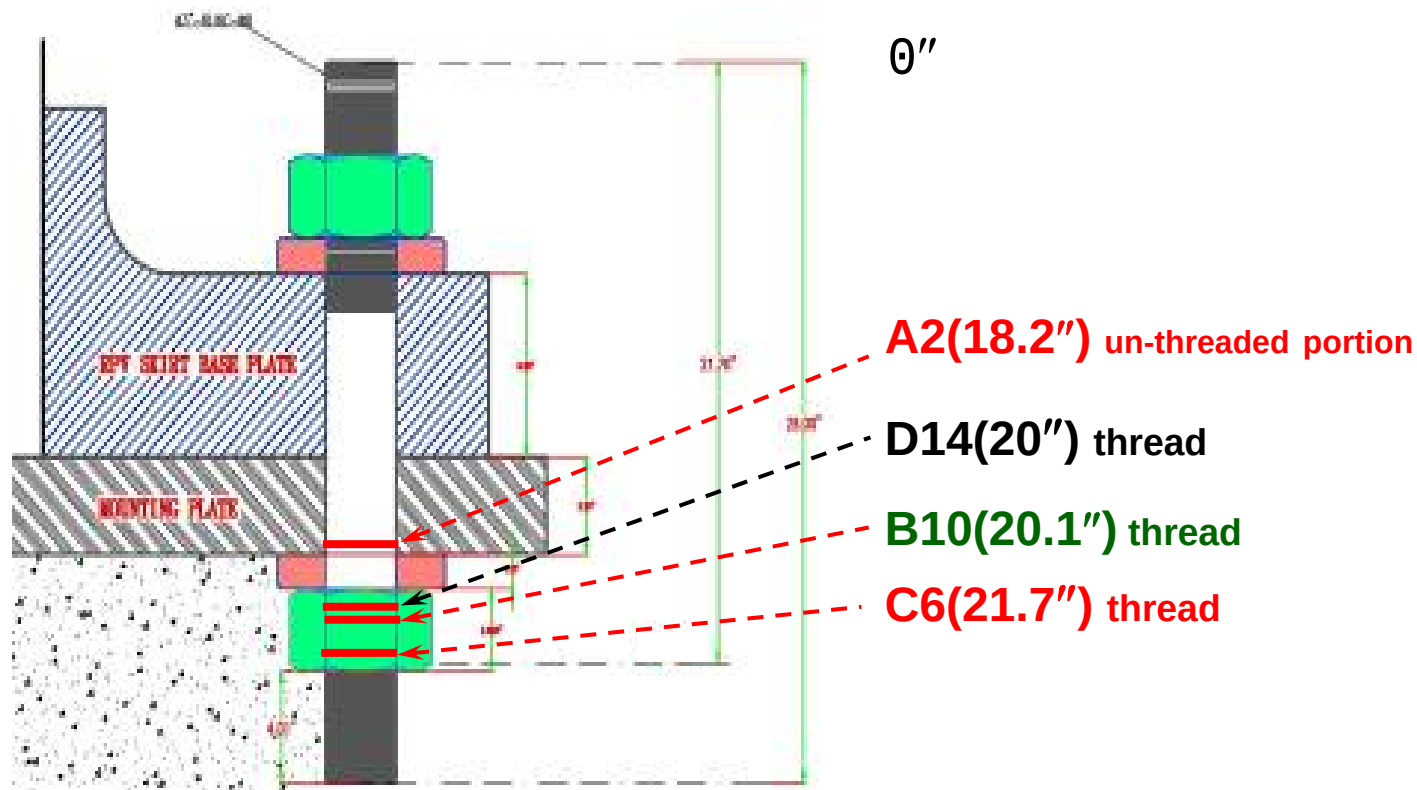
B10 受損(Defected)



螺栓受損位置

Outer ring

Inner ring



受損錨定螺栓(A2, C6, D14及B10)熱室檢驗結果彙整

Cause



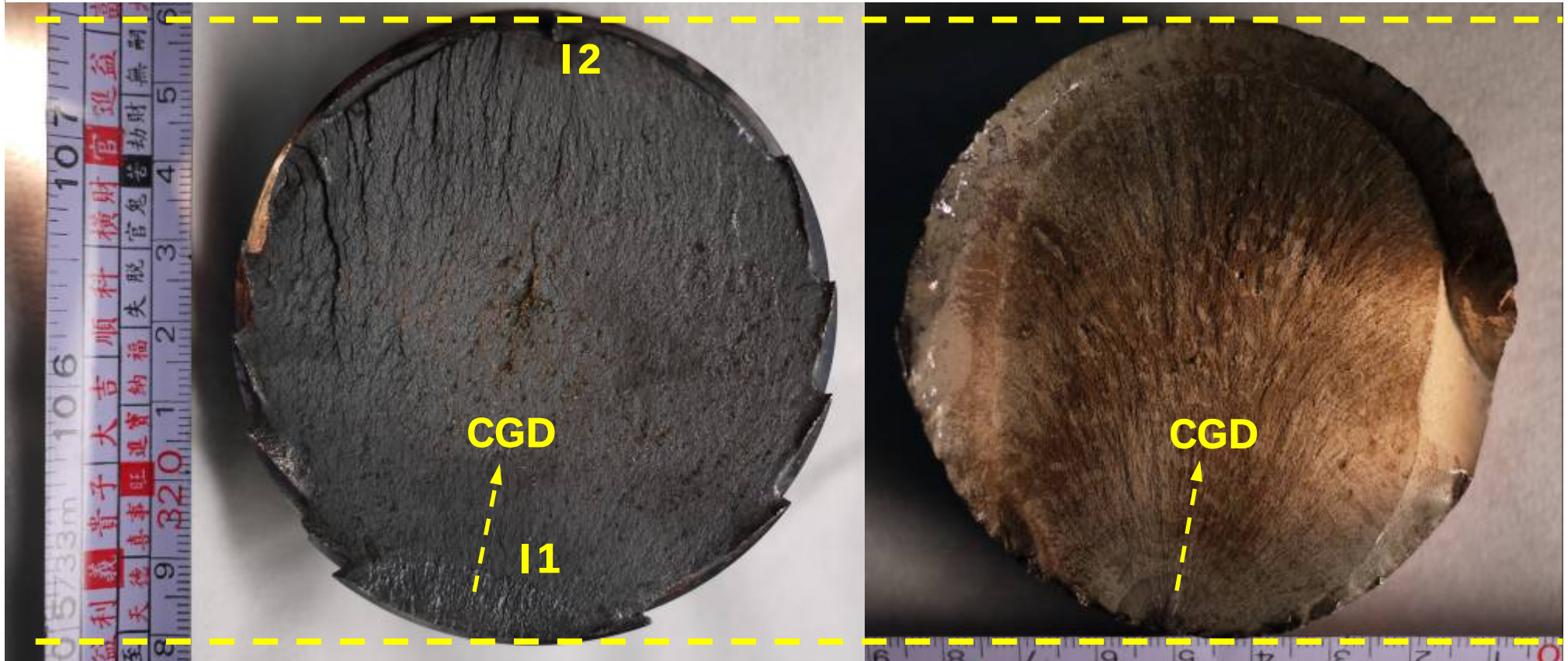
ID	螺栓受損狀態 上螺牙頂點0"	斷口巨觀形貌 Fractography	斷口龜裂形貌 Profile	斷口起裂區形貌 Profile	金相觀察 Profile	機械性質 Ksi	化學成分 Profile
A2	- 螺桿(無螺牙)斷裂 - 位置：18.2"	- 斷裂起裂於單一區域 - 裂紋擴展區平坦平面 - 斷口表面嚴重磨損 - 螺栓邊緣拉斷區為剪力唇(~2個螺牙高度)	- 裂紋萌生：<u>沿晶破裂</u>(~4 mm)；晶面有微韌窩 - 裂紋擴展：<u>韌窩破壞</u>	- 數個裂紋萌生位置 - 裂紋與螺桿表面夾45° - 表面瑕疵(孔洞連結) - 微孔及微裂 - 二次裂紋；氧化物；腐蝕孔(輕微)	- 回火麻田散鐵+殘留沃斯田鐵+析出相 - 硫化物夾雜物 - 二次裂紋分枝不明顯 - 氧化層(~10 μm)	ASME B23 Class 1 165 Ksi*1 符合規範 190(189)*2	ASME SA-540 B23 符合規範
C6	- 下部螺牙斷裂 - 位置：21.7"	- 斷裂起裂於2區域(起裂源相距180°) - 裂紋擴展區平坦斜面(~5個螺牙高度) - 近螺栓中心拉斷區無明顯剪力唇	- 裂紋萌生：<u>沿晶破裂</u>(~6 mm)；晶面有微韌窩 - 裂紋擴展：<u>韌窩破壞</u>	- 數個裂紋萌生位置 - 裂紋⊥螺牙面 - 微孔及微裂 - 二次裂紋；氧化物；腐蝕孔(不明顯)	- 回火麻田散鐵+殘留沃斯田鐵+析出相 - 硫化物夾雜物 - 二次裂紋分枝不明顯 - 氧化層(~5 μm)	ASME B23 Class 1 165 Ksi*1 符合規範 182(175)*2	ASME SA-540 B23 符合規範
D14	- 下部螺牙龜裂 - 位置：20"	- 破裂起裂於單一區域 - 特定區域5個螺牙面出現環向裂紋，相距180°之牙面無對應裂紋 - 裂紋擴展區平坦斜面	- 裂紋萌生：<u>沿晶破裂</u>(~6 mm)；晶面有微韌窩 - 裂紋擴展：<u>韌窩破壞</u>	- 數個裂紋萌生位置 - 裂紋⊥螺牙面 - 表面缺陷(外力舊傷) - 微孔及微裂 - 二次裂紋；氧化物；腐蝕孔(明顯)	- 回火麻田散鐵+殘留沃斯田鐵+析出相 - 硫化物夾雜物 - 二次裂紋分枝明顯 - 氧化層(~10 μm)	ASME B23 Class 1 165 Ksi*1 符合規範 177(174)*2	ASME SA-540 B23 符合規範
B10	- 下部螺牙損傷 - 位置：20.1"	- 破裂起裂於單一區域 - 裂紋擴展區為斜面(<1個螺牙高度)	- 裂紋萌生：<u>沿晶破裂</u>(0.5~1 mm)；晶面有微韌窩 - 裂紋擴展：<u>韌窩破壞</u>	- 數個裂紋萌生位置 - 裂紋⊥螺牙面 - 微孔及微裂 - 二次裂紋；氧化物	- 回火麻田散鐵+殘留沃斯田鐵+析出相 - 硫化物夾雜物 - 二次裂紋分枝明顯 - 氧化層(10~15 μm)	ASME B23 Class 1 165 Ksi*1 未達規範 158(160)*2	ASME SA-540 B23 符合規範

*1: ASME SA-540 B23 Class I (to 3", included) minimum tensile strength : 165 Ksi (Note: [RG 1.65](#) 抗SCC限值, $\sigma_t \leq 170\text{Ksi}$)

*2: While data were obtained by INER from hardness tests, data in parenthesis were obtained by ITRI from tensile tests.



斷裂(Broken)螺栓 A2 & C6



1EOC22 (C6)

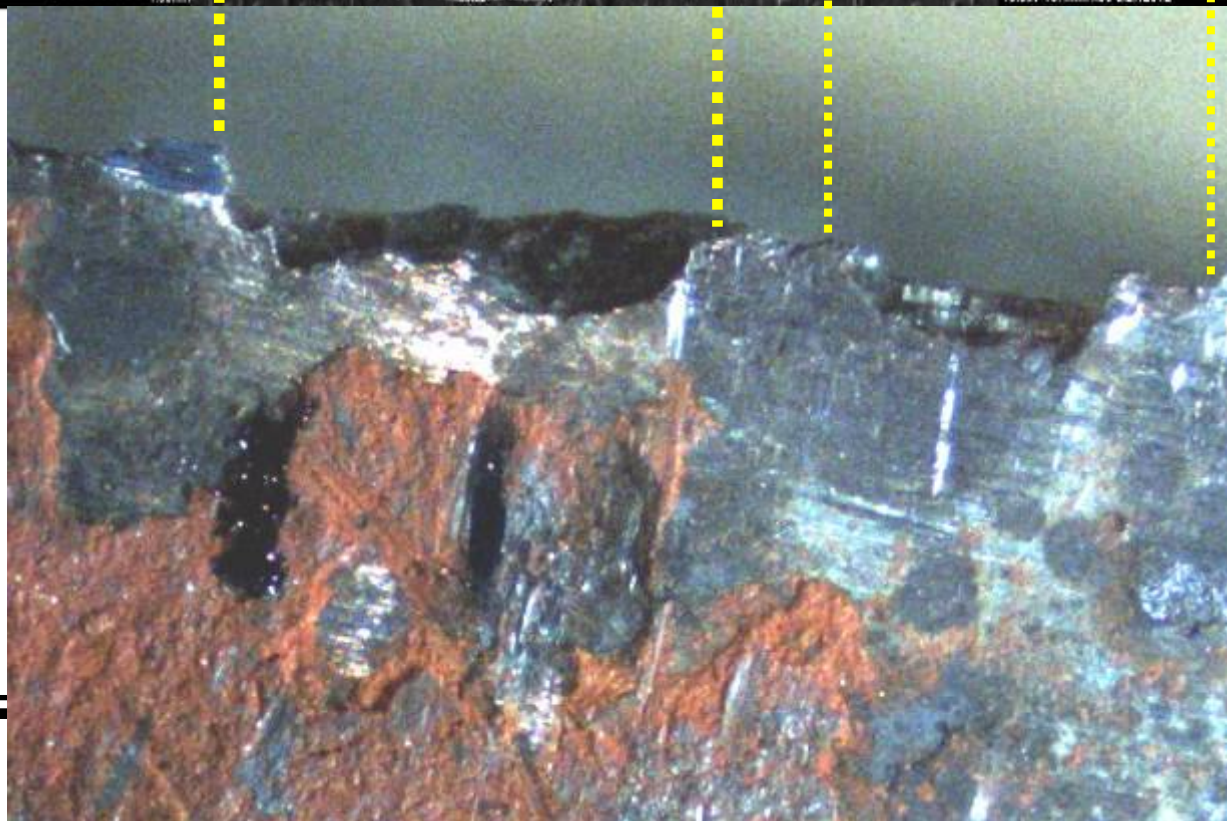
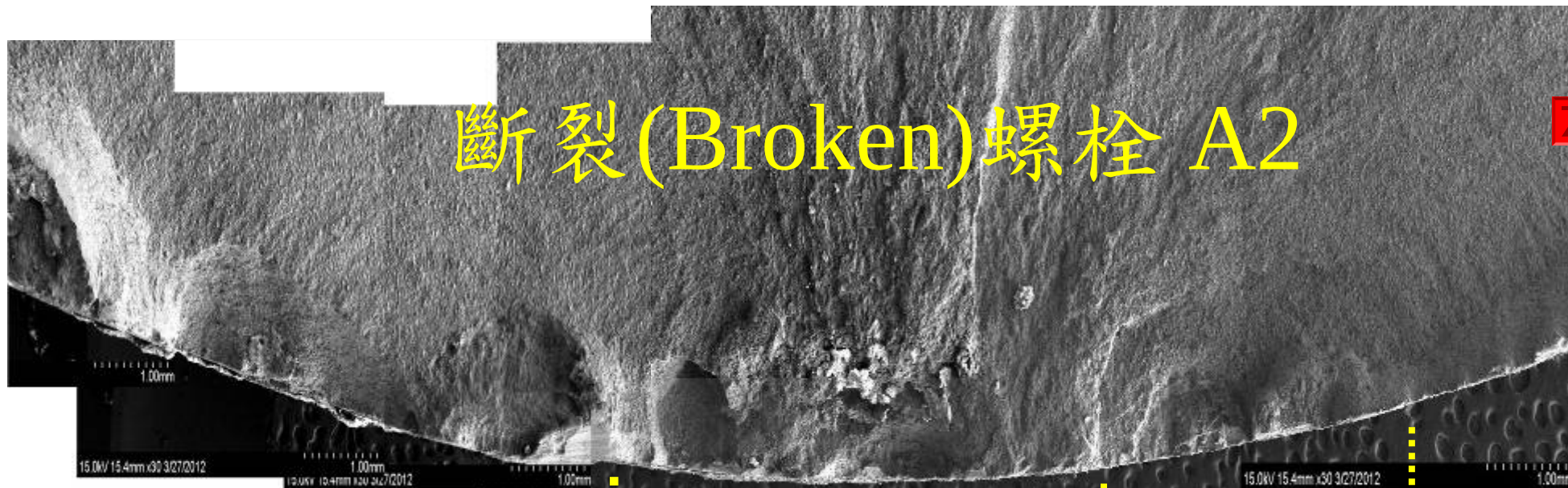
1EOC22 (A2)



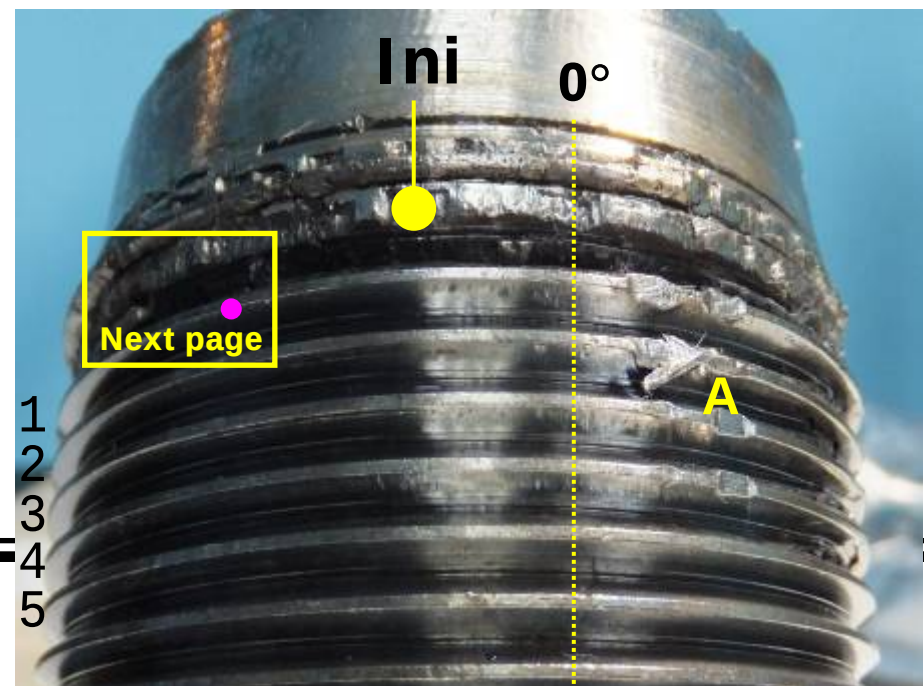
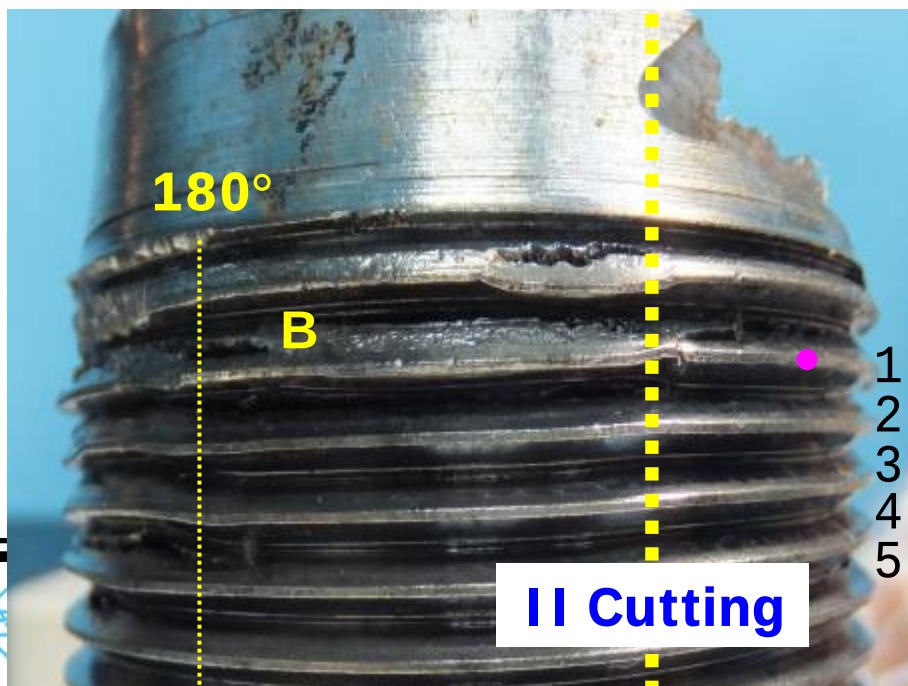
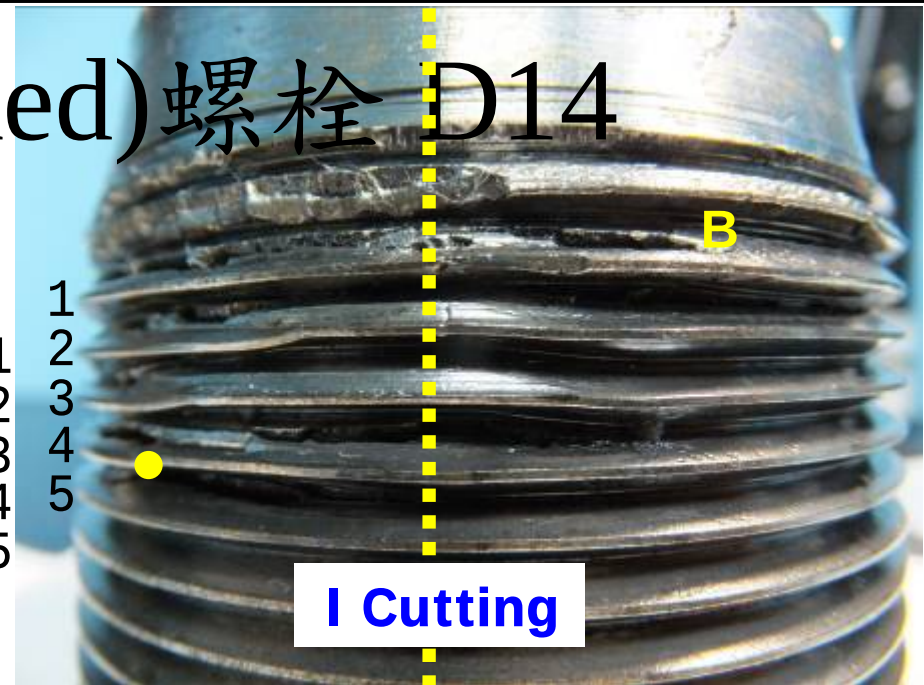
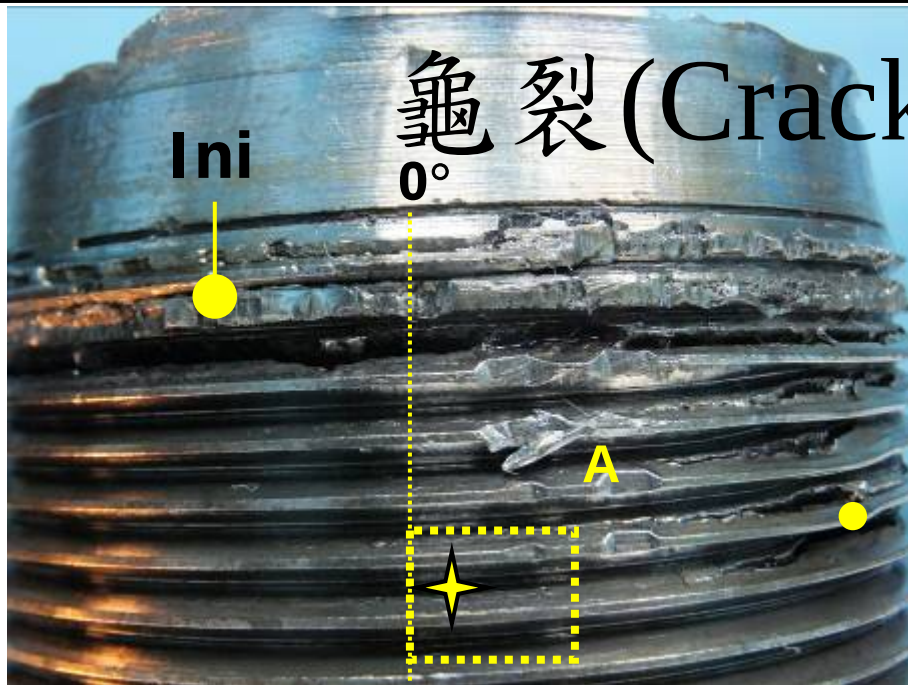
斷裂(Broken)螺栓 A2



斷裂(Broken)螺栓 A2

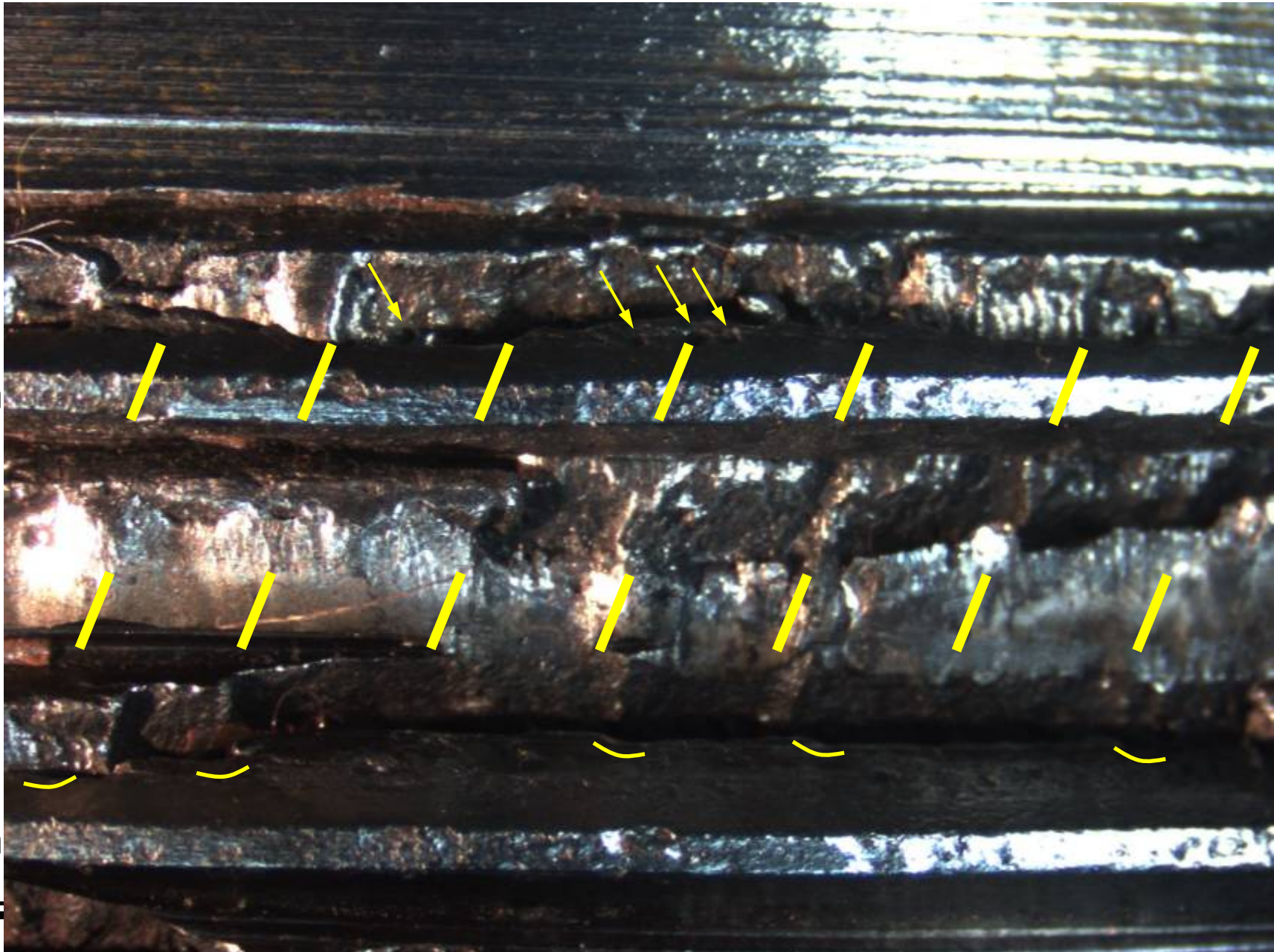


龜裂(Cracked)螺栓 D14



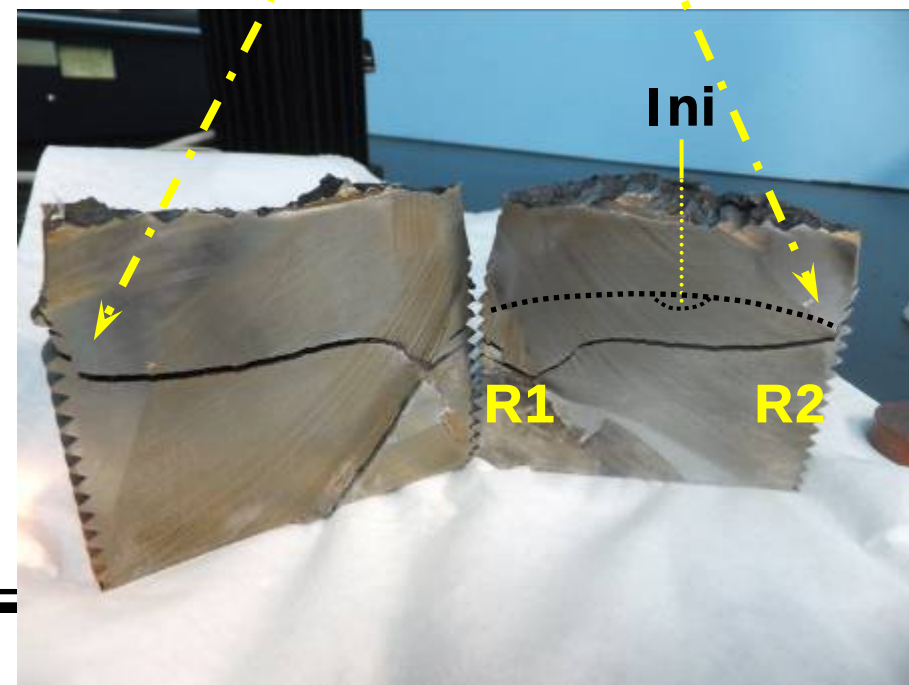
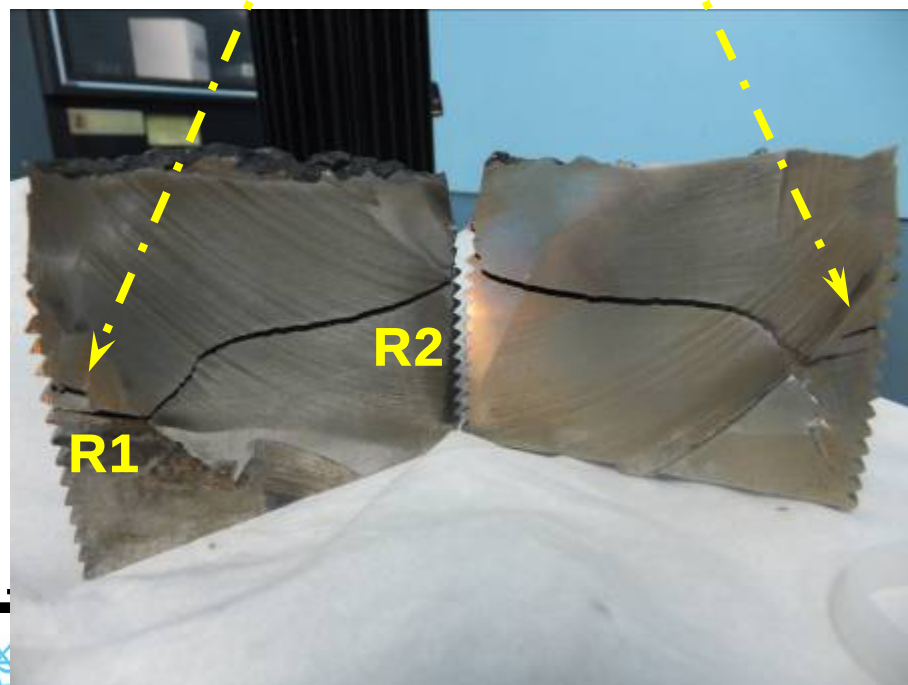
Tooth

Tooth

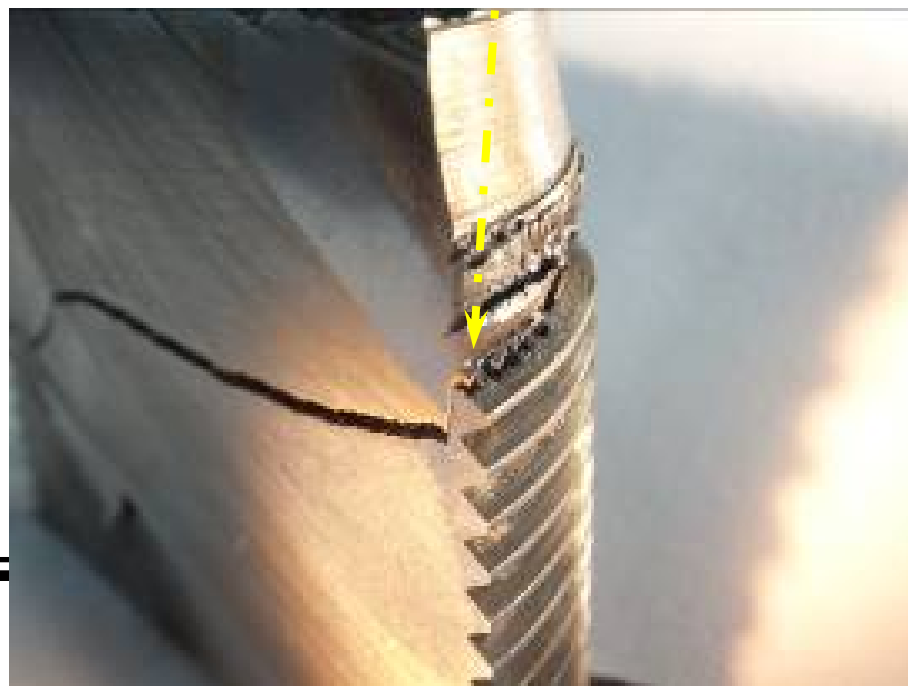
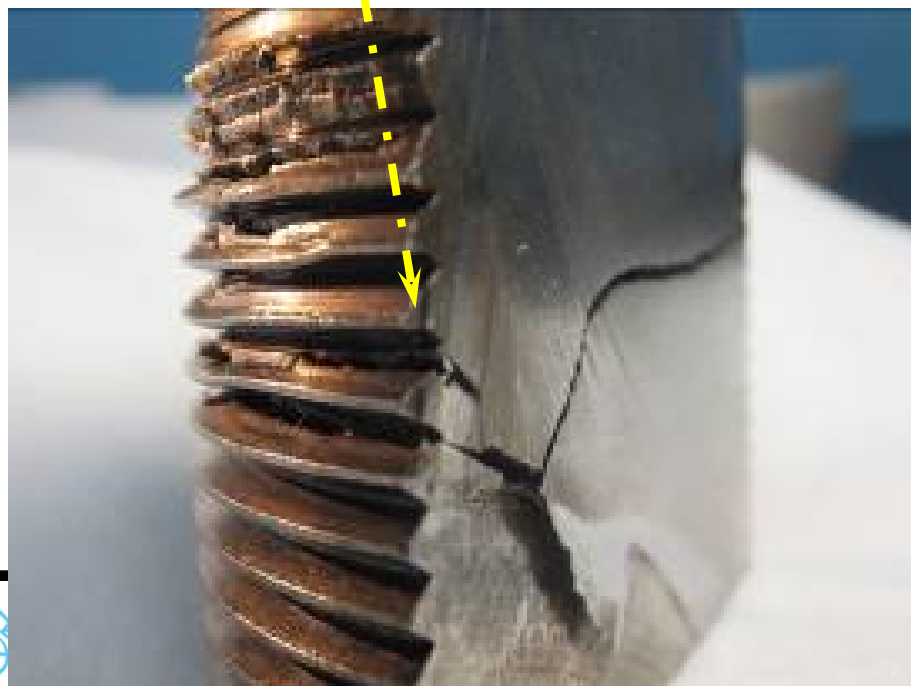
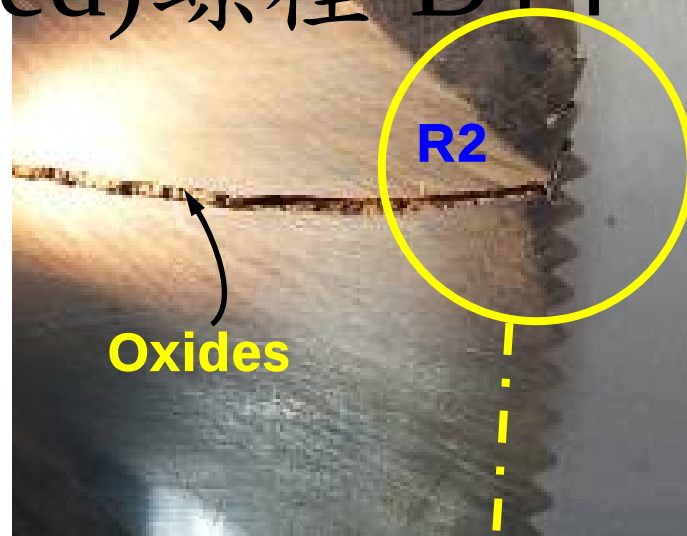
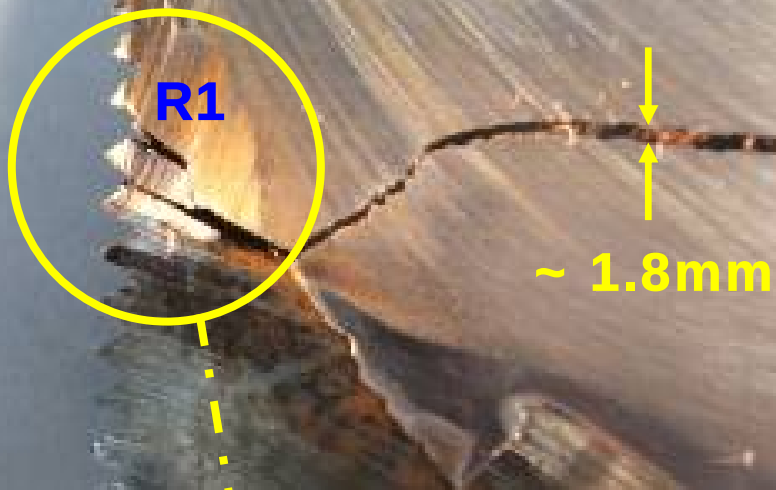


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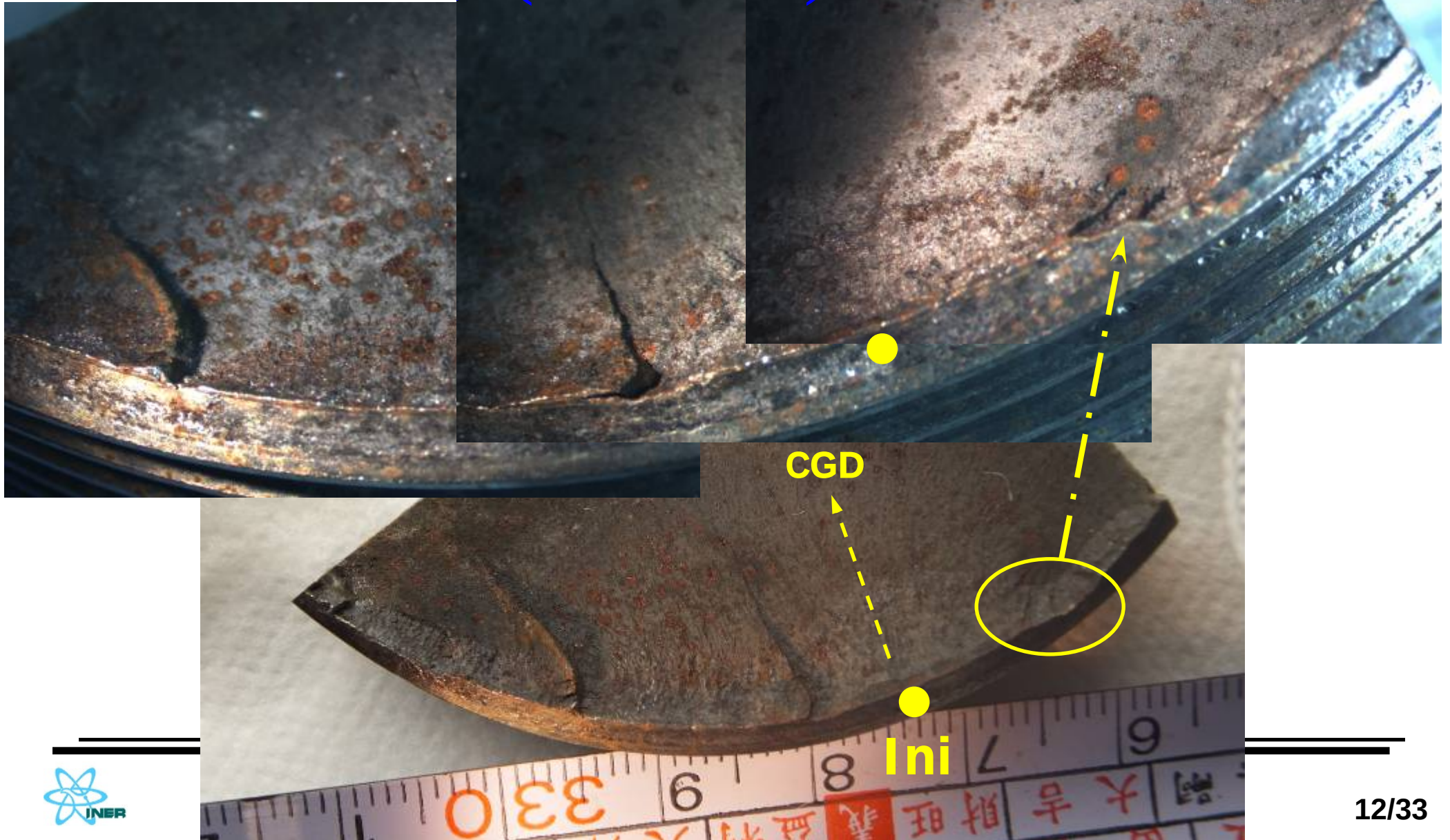




龜裂(Cracked)螺栓 D14

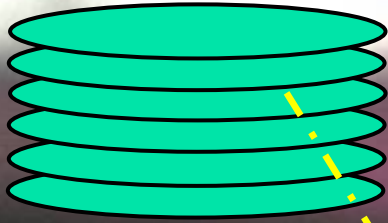


龜裂(Cracked)螺栓 D14



受損(Defected)螺栓 B10

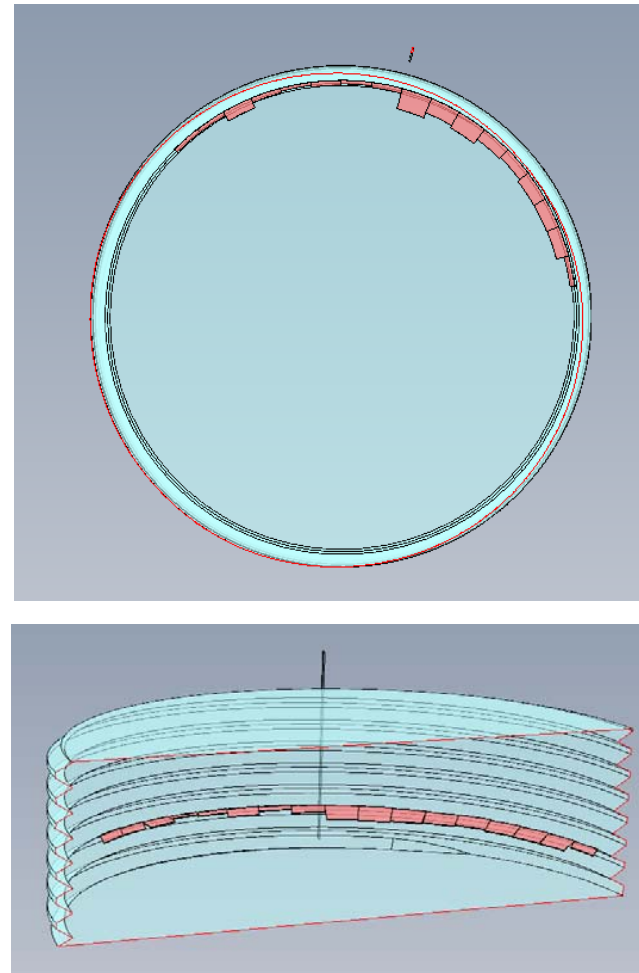
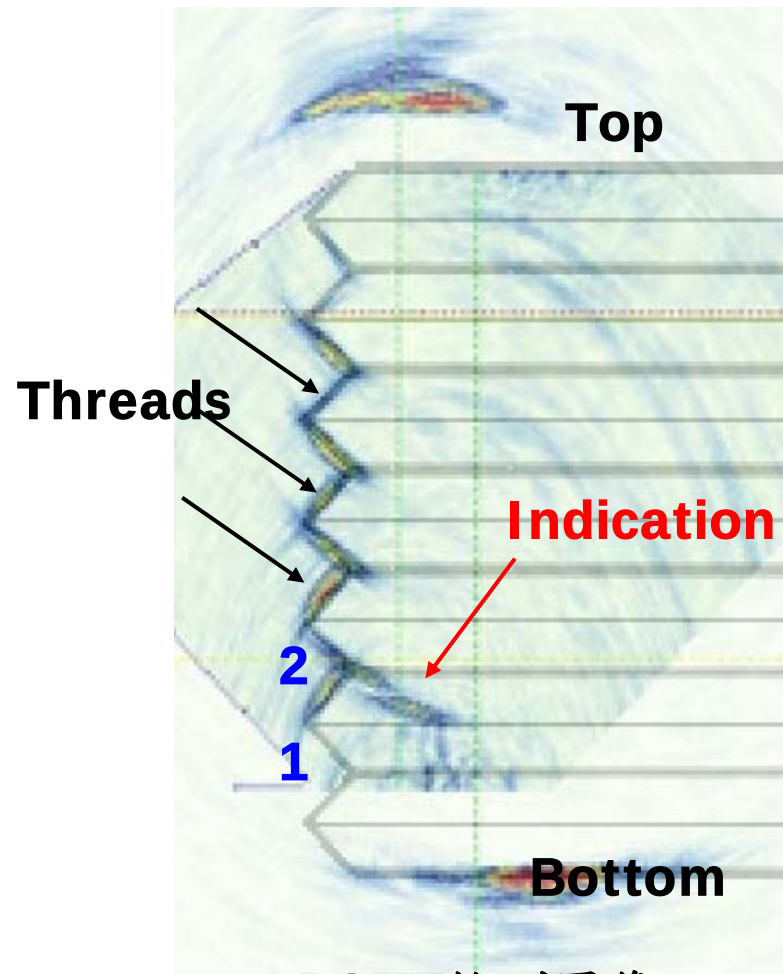
Thread tooth



Thread root

Thread tooth

受損(Defected)螺栓 B10

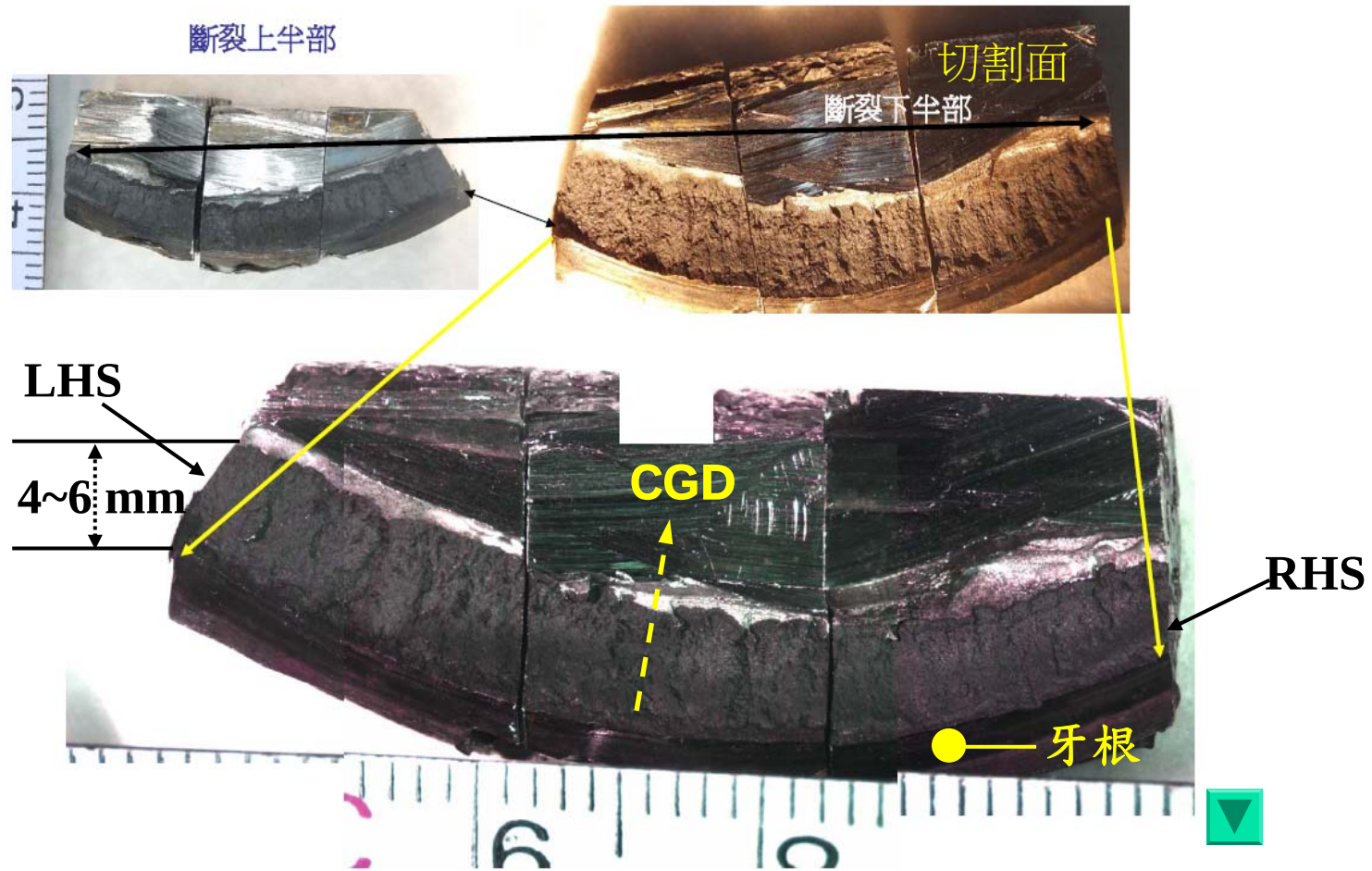


裂紋說明

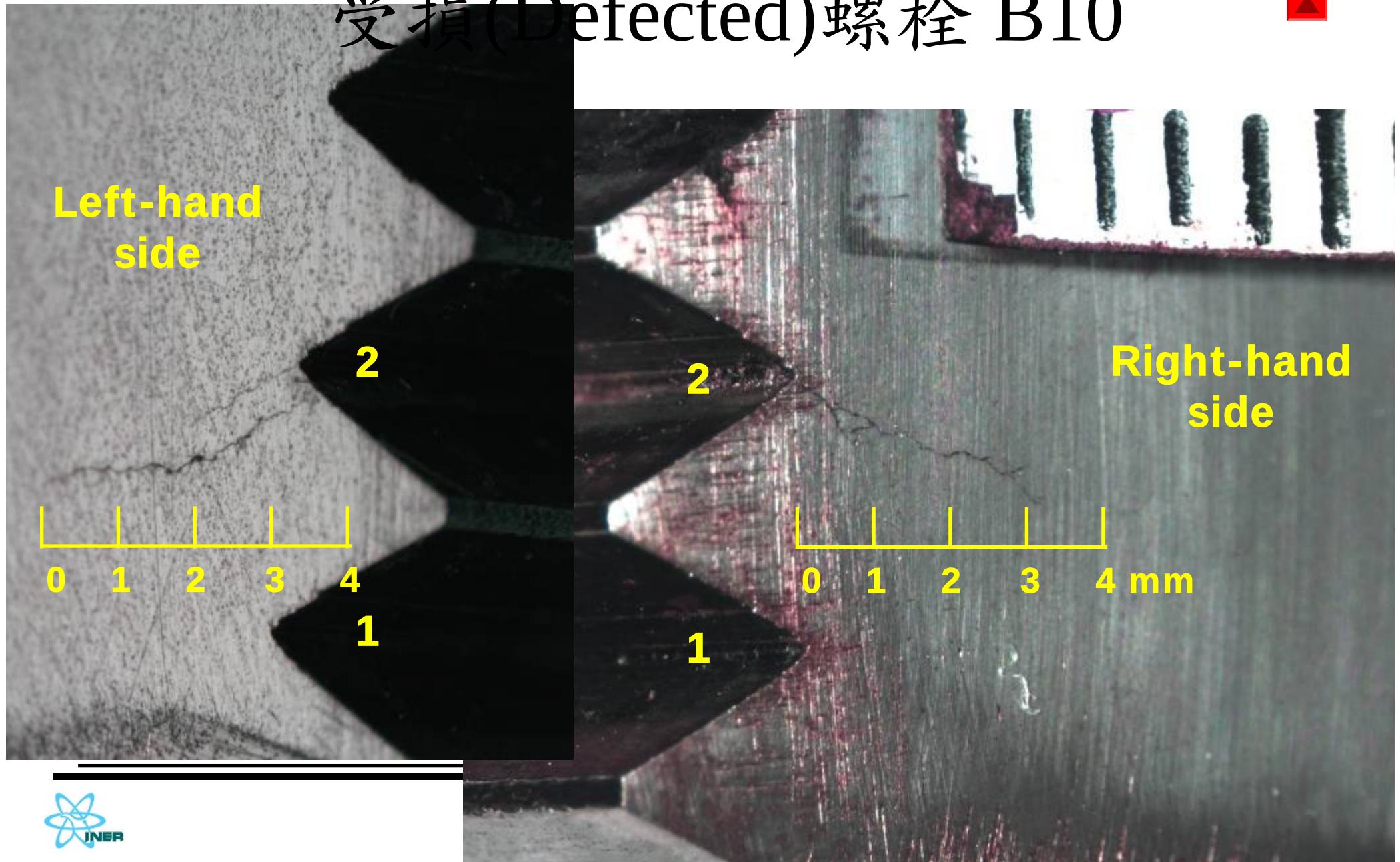
- 傾斜向下發展；
- 圓周向弧長 95mm；
- 水平徑向最深約5mm (明確區+陰影區)。



受損(Defected)螺栓 B10



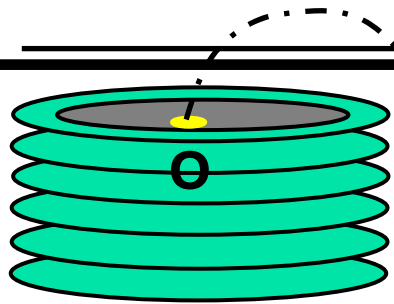
受損(Defected)螺栓 B10



Element	Chemical Requirements (%)							
	A2* ^B	C6* ^B	D14* ^{P,Ckcd}	B10* ^{In}	B13* ^{In}	C9* ^{In}	D11* ^{In}	B23 (E-4340-H)
C	0.43	0.46	0.385	0.399	0.388	0.379	0.382	0.37-0.44* ¹
Mn	0.74	0.75	0.73	0.68	0.75	0.76	0.74	0.60-0.95
P	0.006	0.01	0.01	0.01	0.01	0.01	0.01	0.025(max)
S	0.013	0.024	0.024	0.0169	0.0228	0.023	0.021	0.025(max)
Si	0.26	0.28	0.29	0.31	0.26	0.26	0.29	0.15-0.35
Cr	0.79	0.78	0.73	0.82	0.76	0.76	0.77	0.65-0.95
Ni	1.77	1.73	1.64	1.82	1.67	1.71	1.7	1.55-2.00
Mo	0.23	0.23	0.2	0.23	0.21	0.21	0.22	0.20-0.30
V	<0.004	<0.004	<0.01	<0.01	<0.01	<0.01	<0.01	

*1: ASME SA540 規範允許偏差為±0.02%

*B: 斷裂(Broken), *PCKcd: 部分龜裂(Partial Cracked), *In: 裂紋指示(Crack Indication)



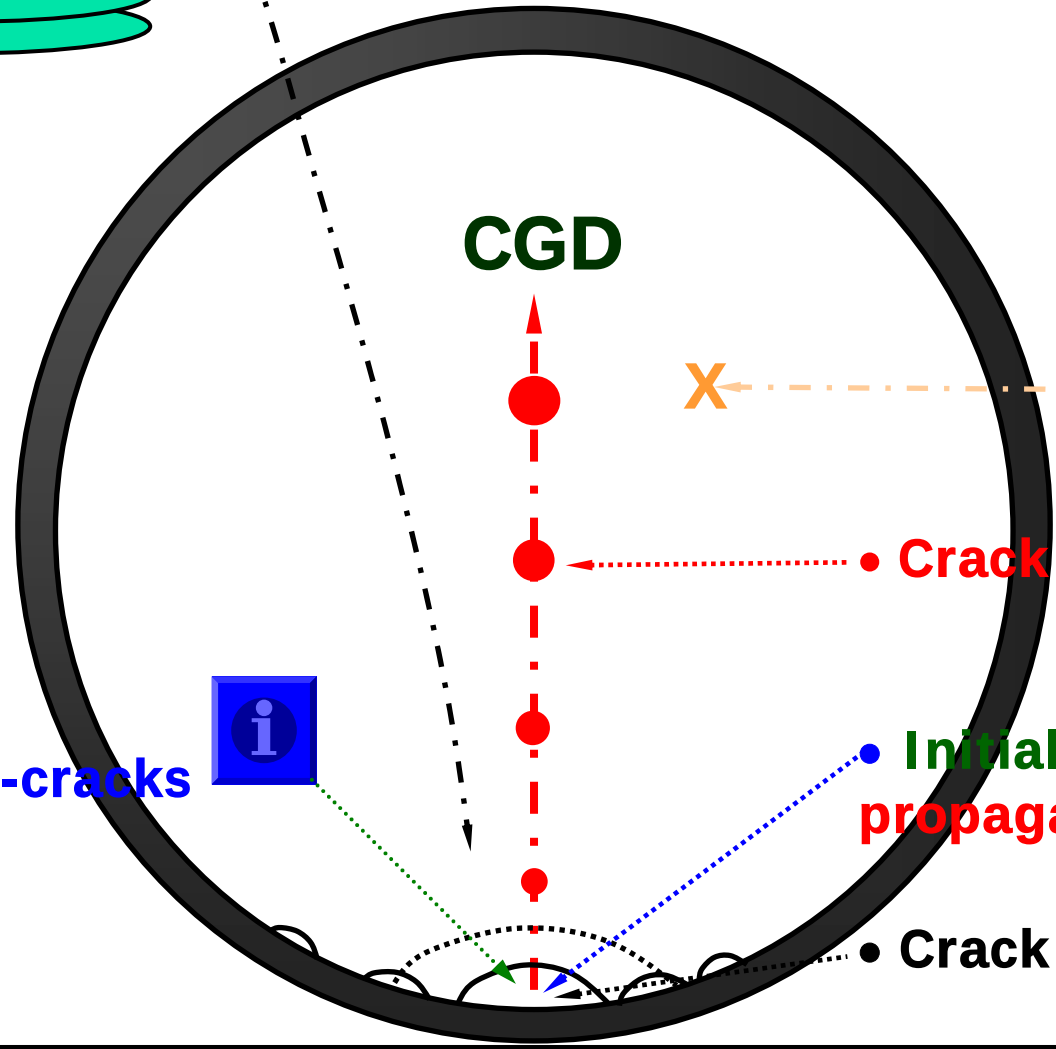
受損螺栓斷面分析



Profile



Cause



- Voids
- micro-cracks

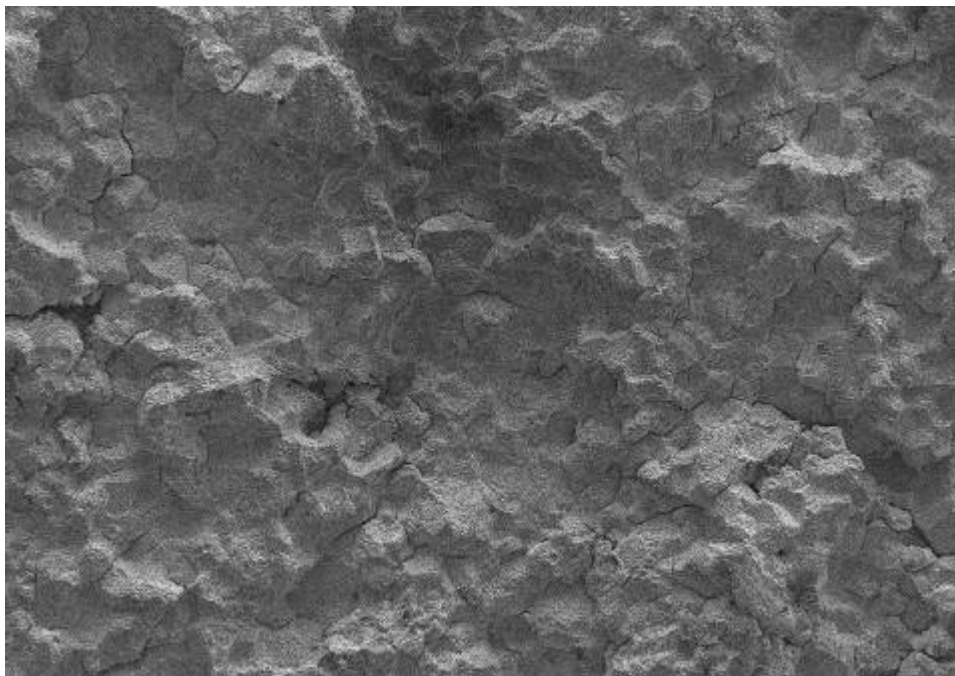
Local zone
(A2 only)

Crack propagation

Initial stage of crack
propagation

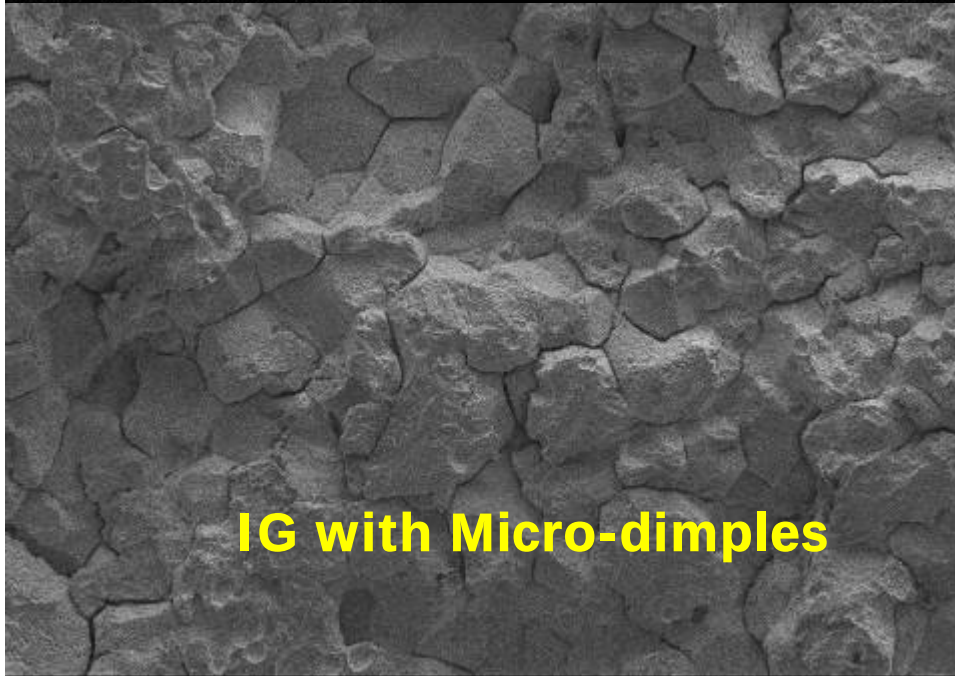
Crack initiation





5.0kV 13.0mm x500 5/2/2012

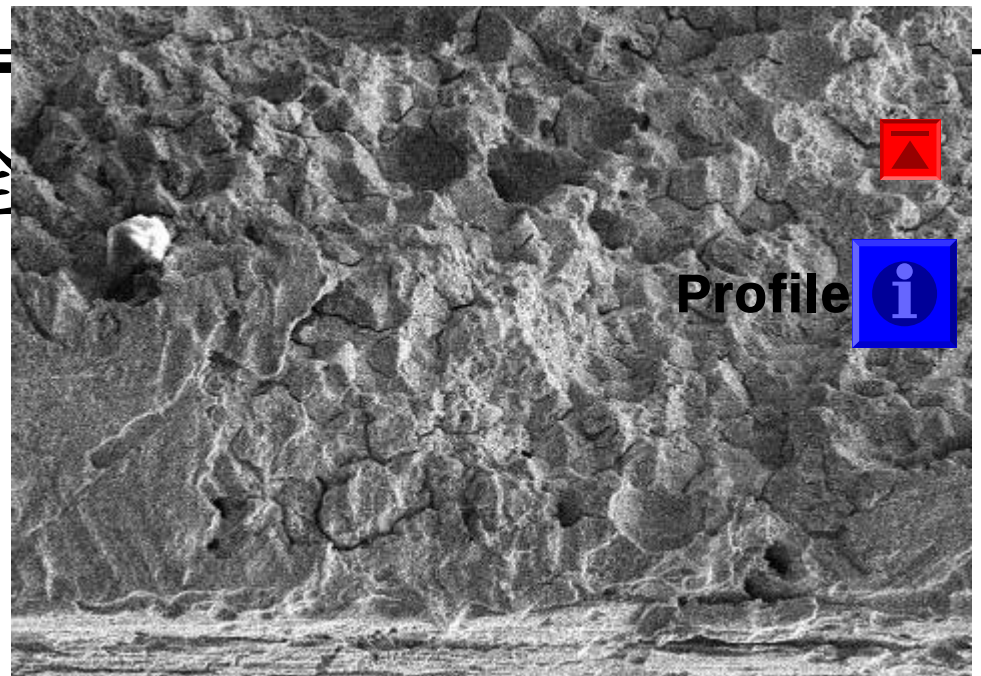
100um



IG with Micro-dimples

5.0kV 13.0mm x1.00k 5/2/2012

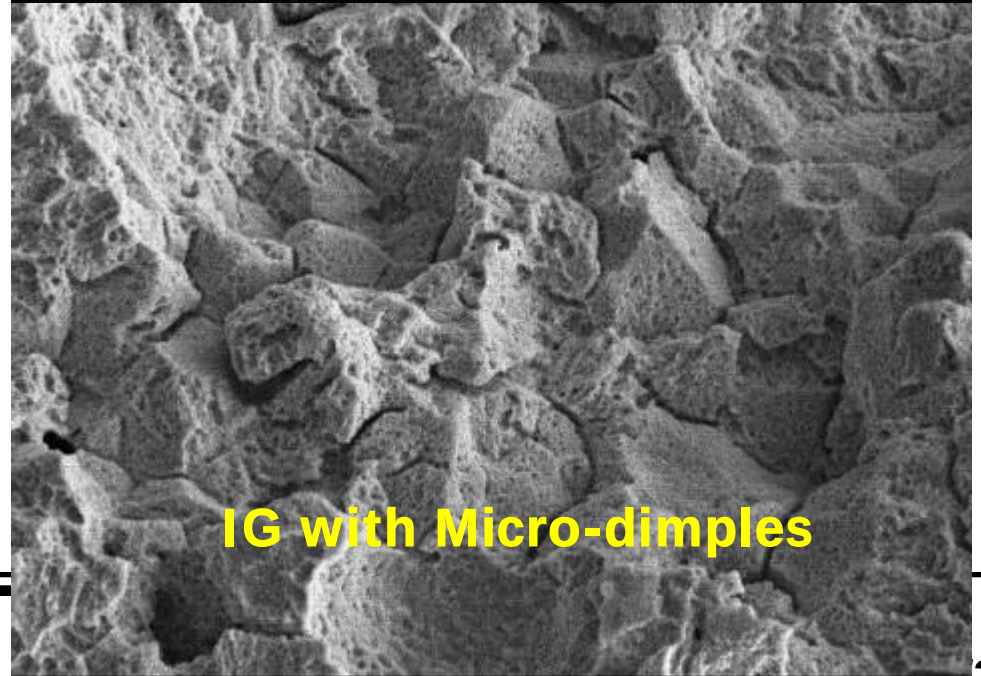
50.0um



Profile

15.0kV 14.9mm x500 5/1/2012

100um

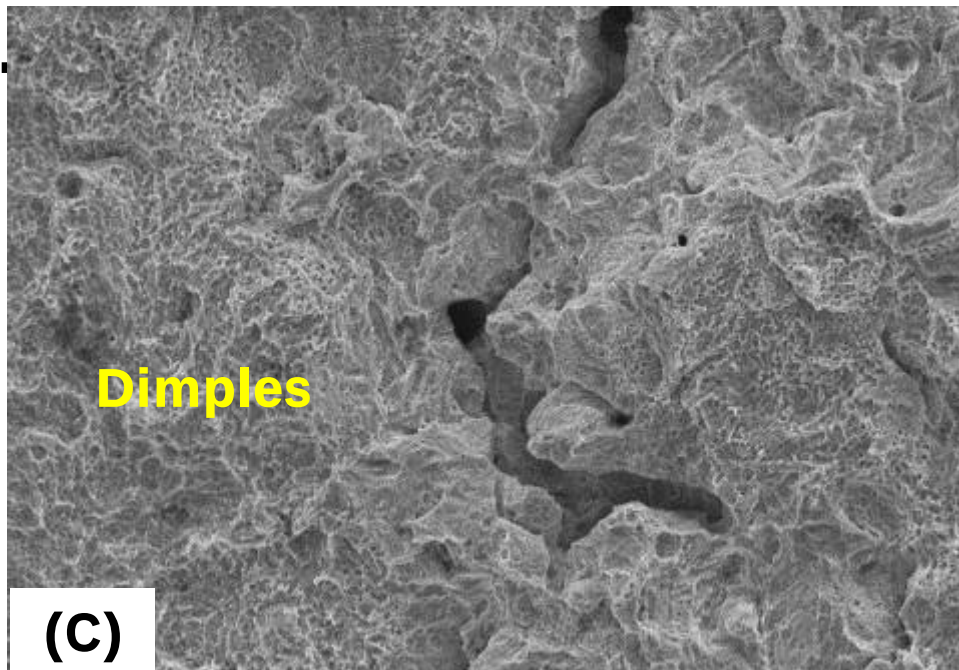


IG with Micro-dimples

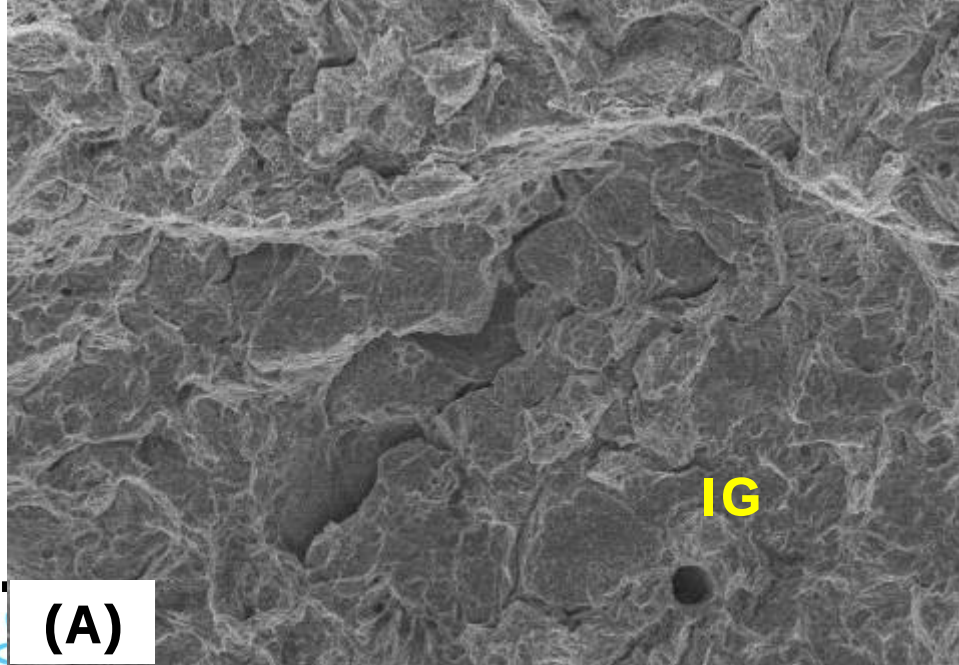
15.0kV 14.9mm x1.50k 5/1/2012

30.0um

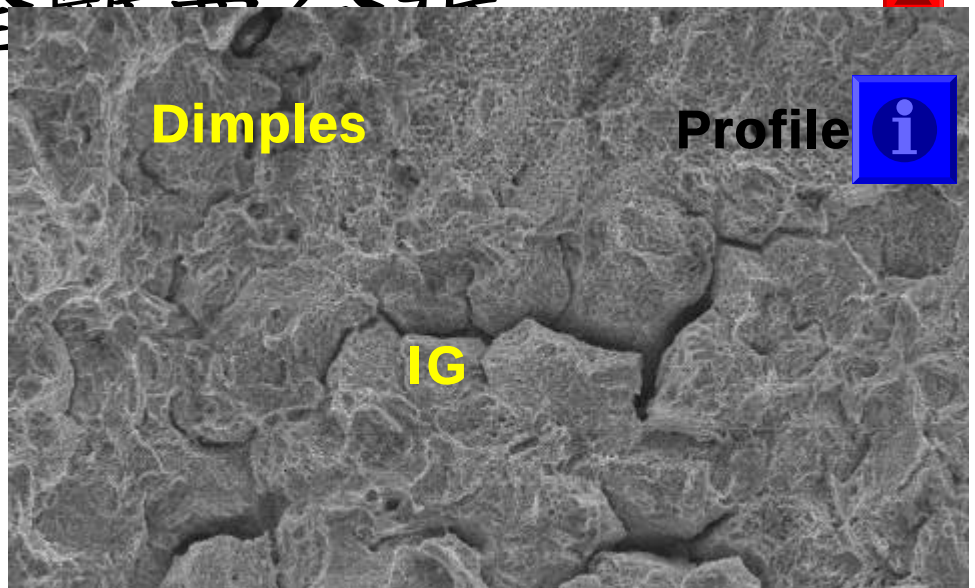
斷石八七



15.0kV 11.5mm x1.00k 5/1/2012 50.0um



15.0kV 11.9mm x1.00k 5/1/2012 50.0um



15.0kV 11.9mm x1.00k 5/1/2012 50.0um

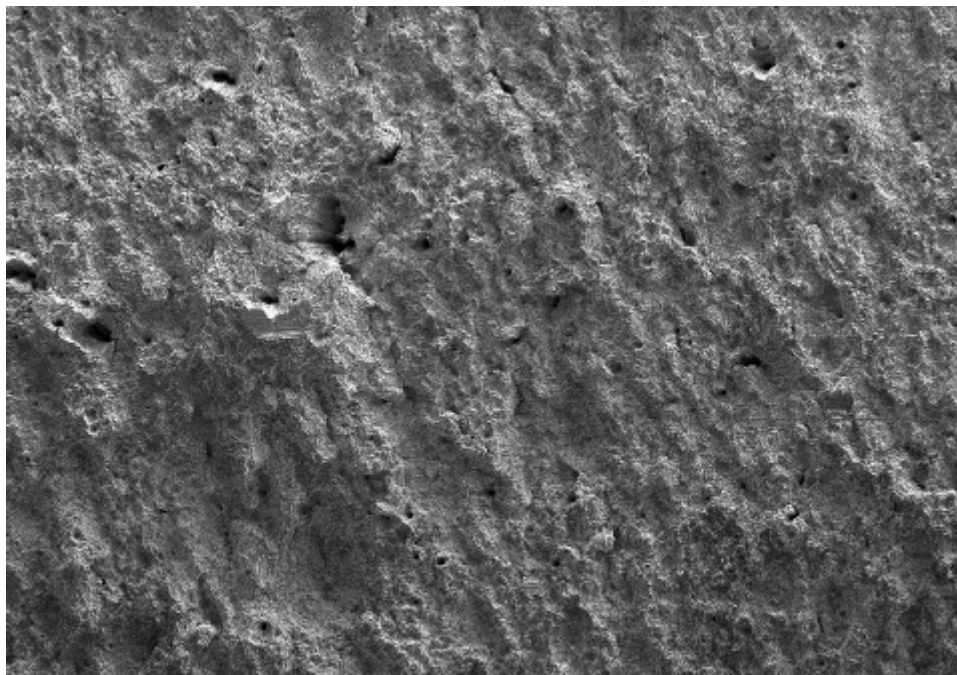
CGD



(C) Dimples

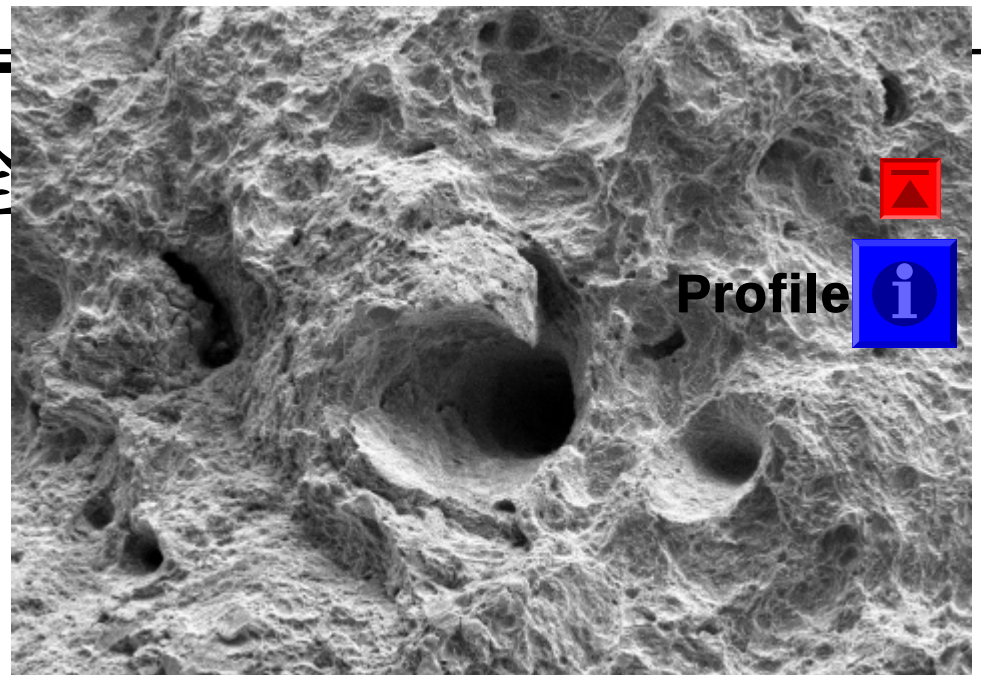
(B) IG+Dimples

(A) IG Cracking



5.0kV 8.0mm x100 4/30/2012

500um



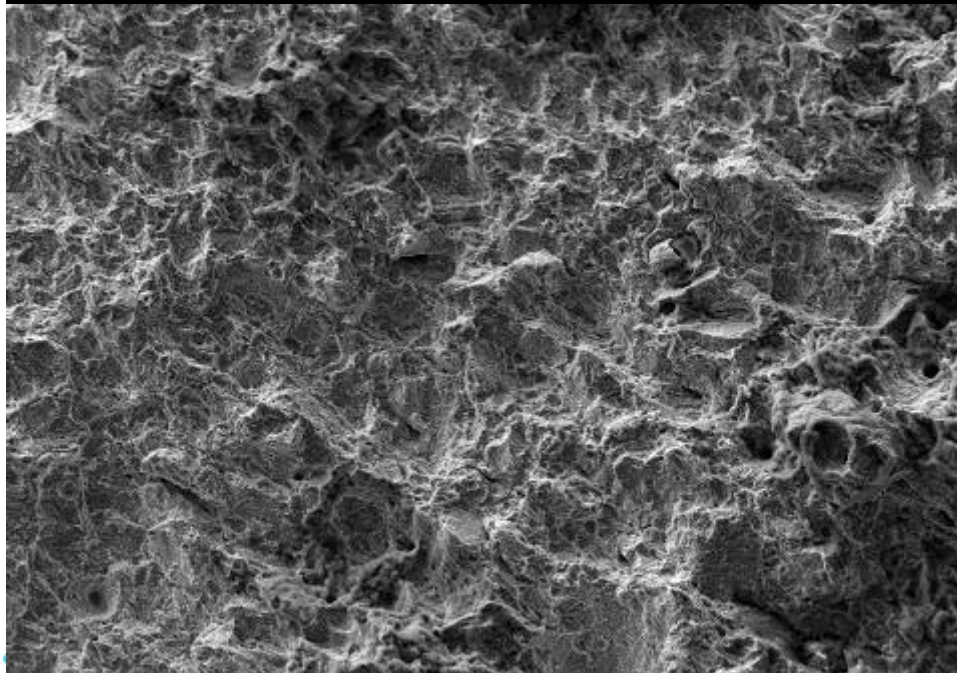
5.0kV 8.0mm x1.50k 4/30/2012



Profile

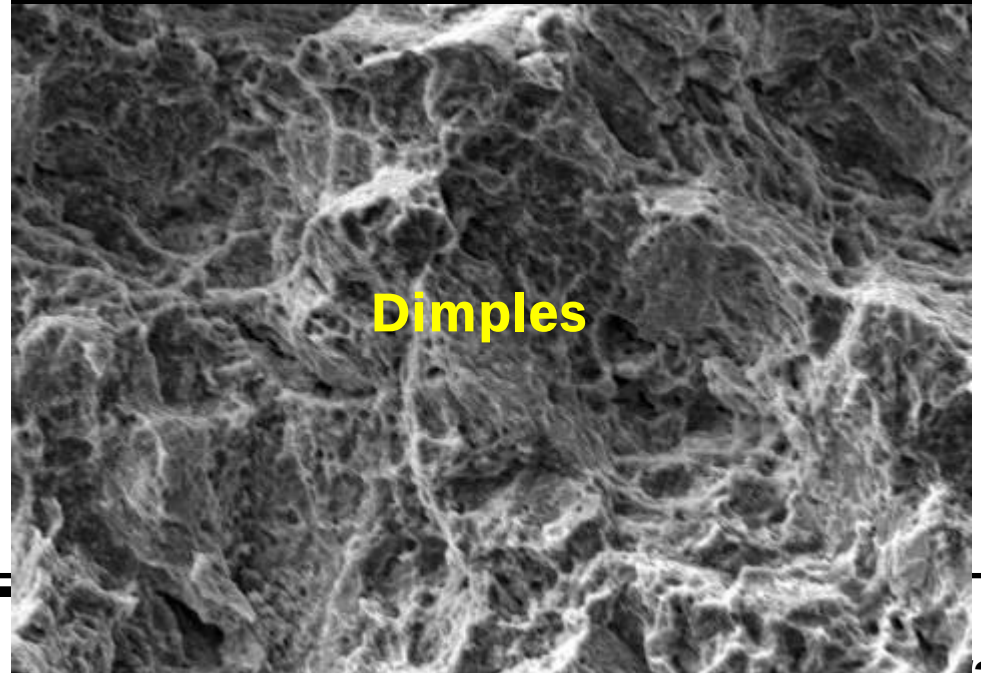


30.0um



15.0kV 15.5mm x500 3/27/2012

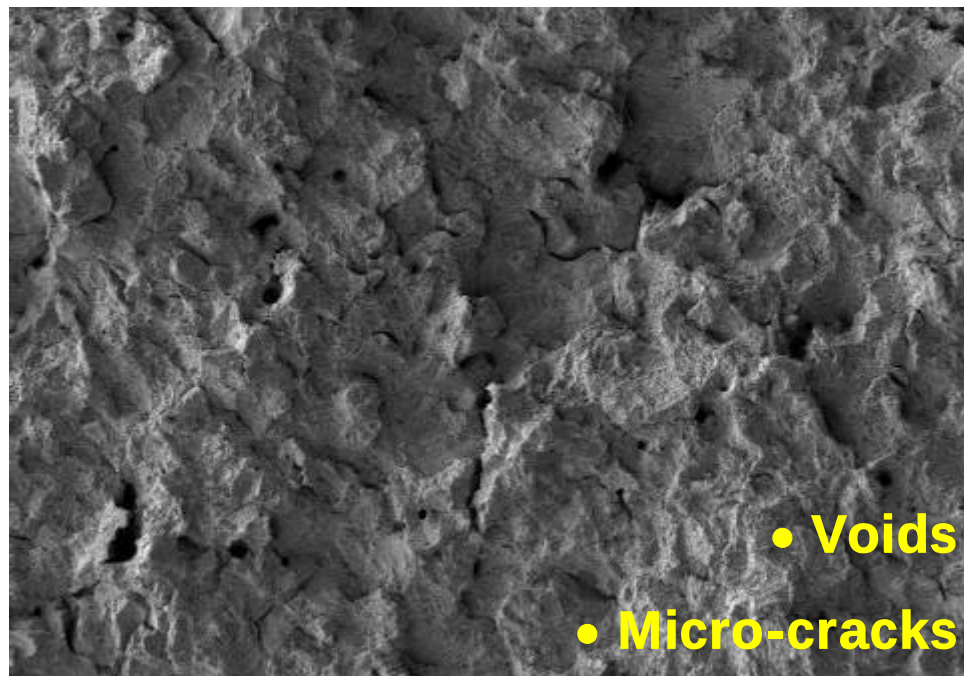
100um



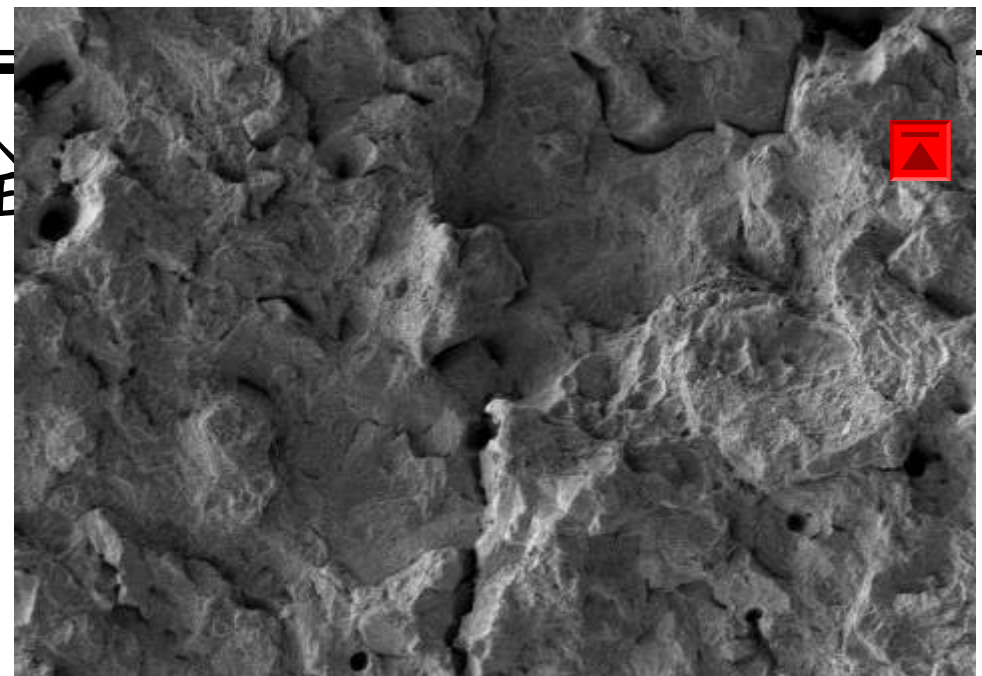
15.0kV 15.5mm x2.00k 3/27/2012

20.0um

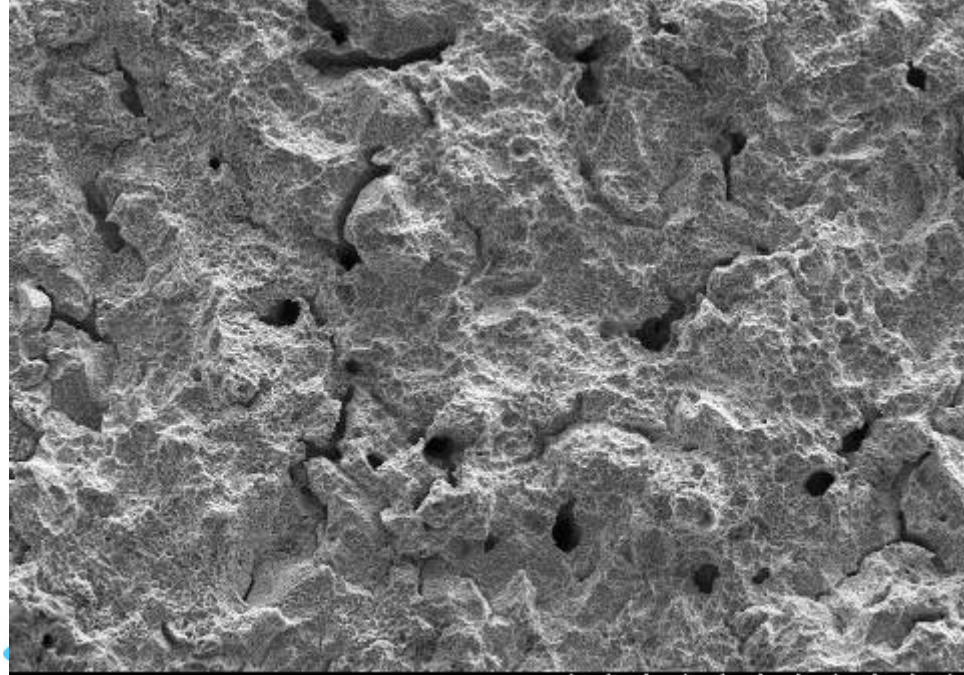
Dimples



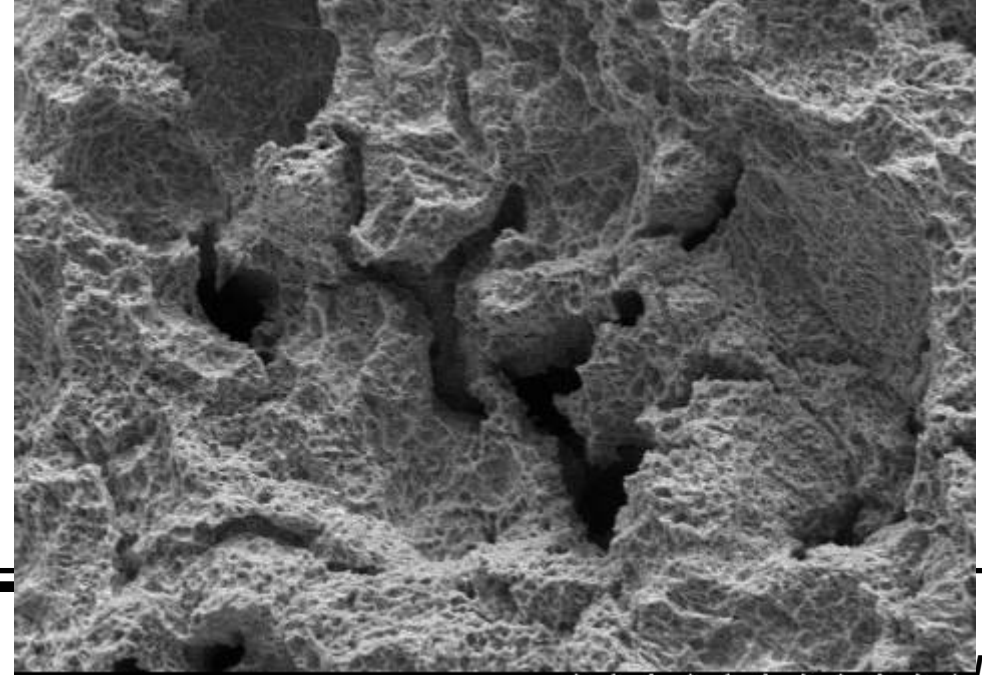
4.0kV 9.2mm x500 3/29/2012 100μm



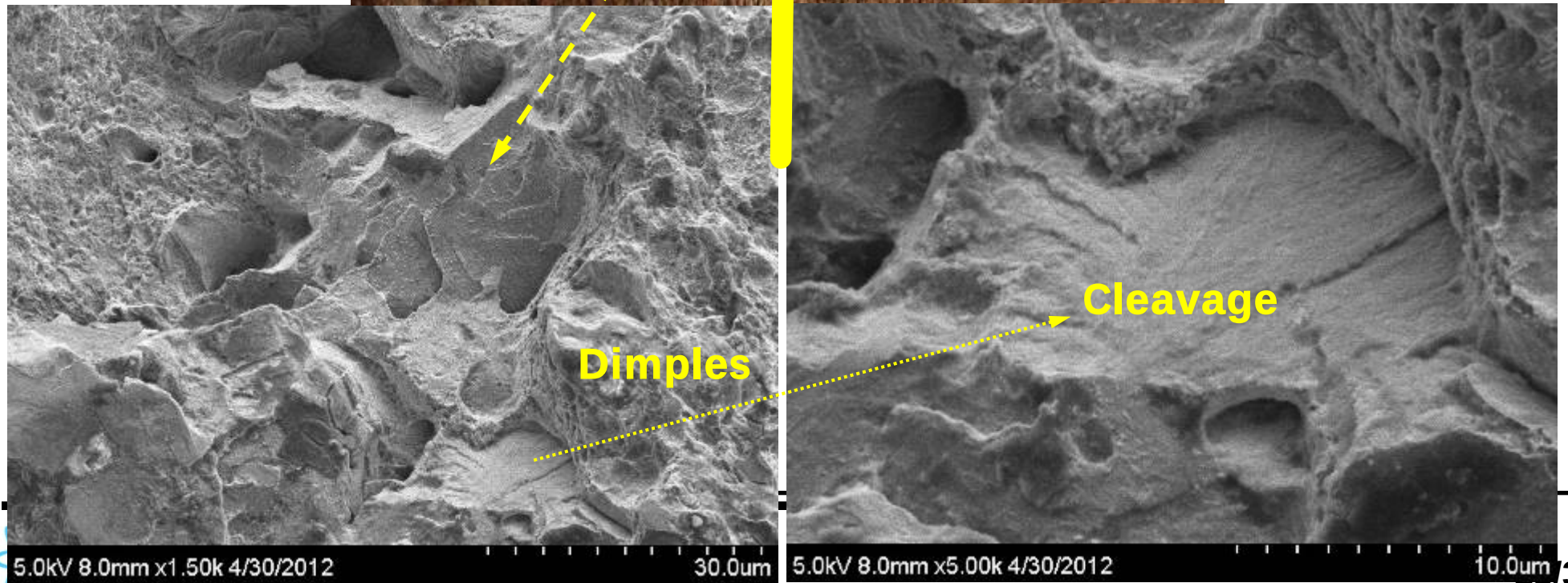
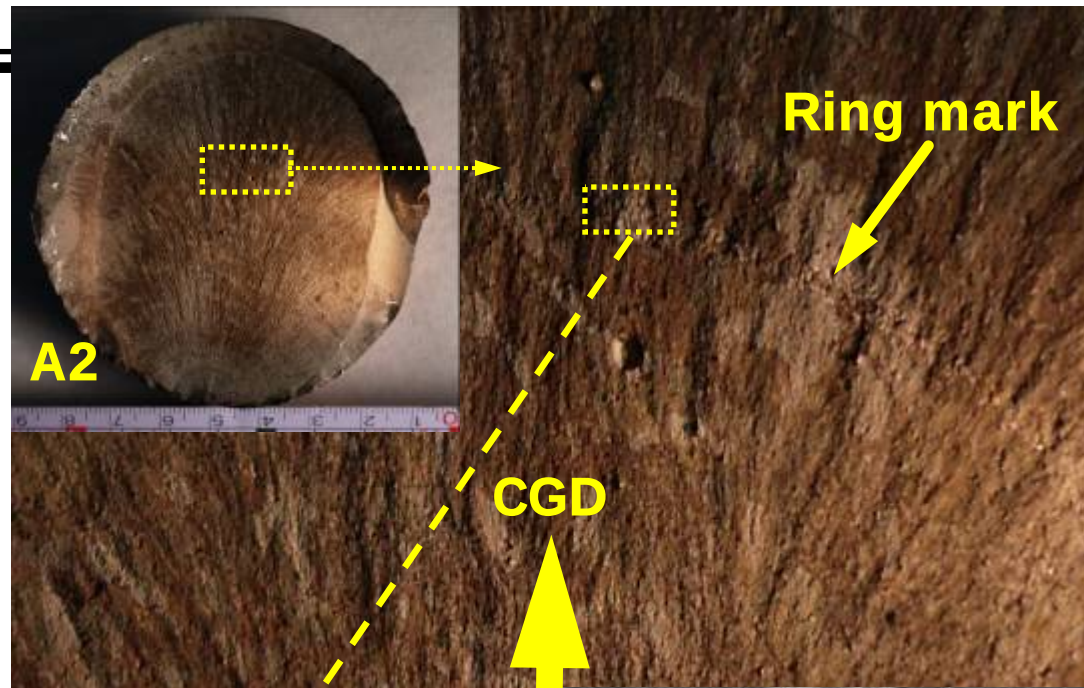
4.0kV 9.2mm x1.00k 3/29/2012 50.0μm

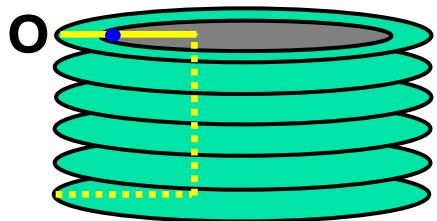


15.0kV 11.9mm x500 5/1/2012 100μm



15.0kV 15.3mm x1.00k 5/1/2012 50.0μm





受損螺栓縱剖面分析



Fratography

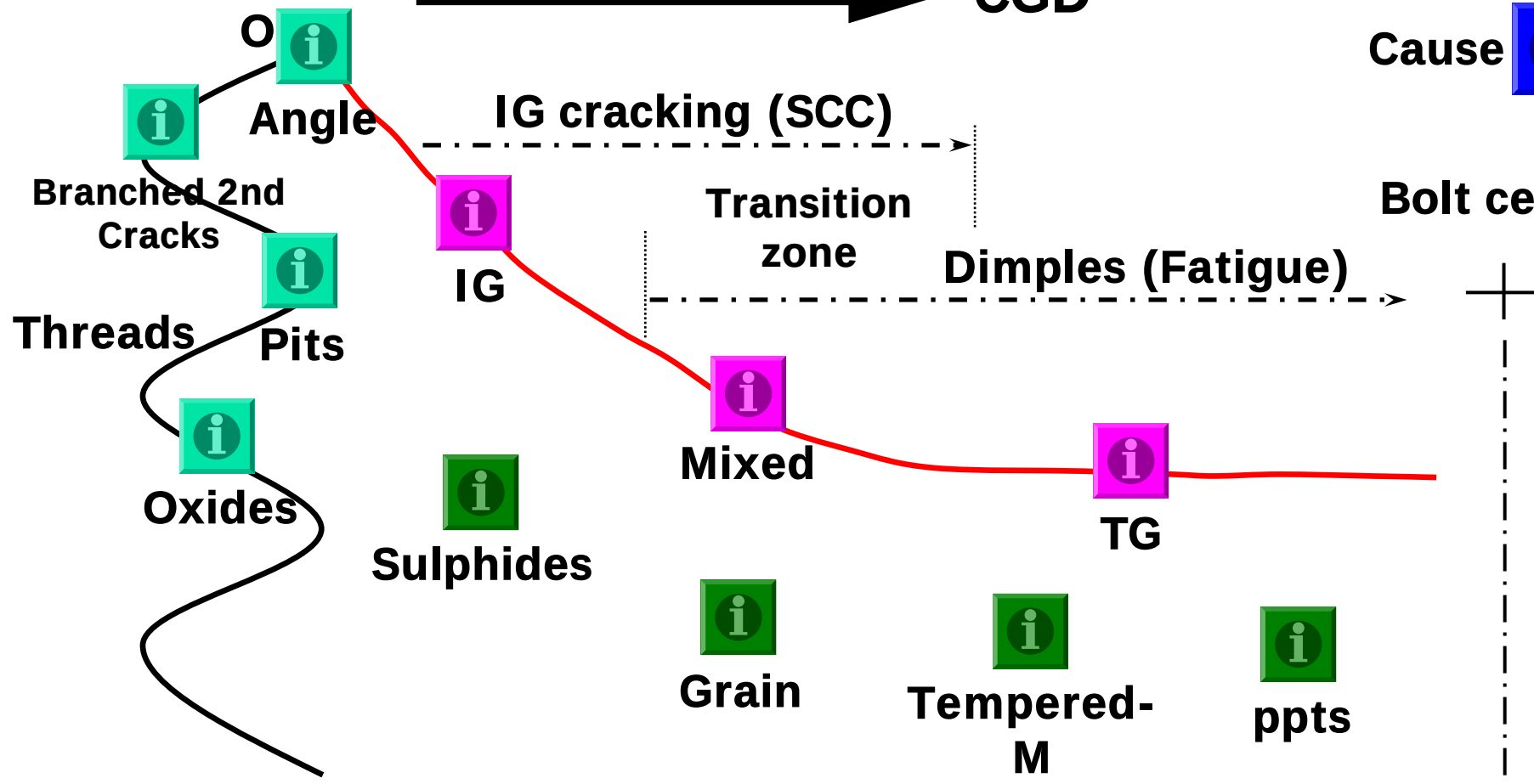


Cause



CGD

Bolt center



受損螺栓縱剖面分析

A2

15.0kV x40 3/30/2012

1.00mm

C6

4.0kV 9.3mm x30 4/7/2012

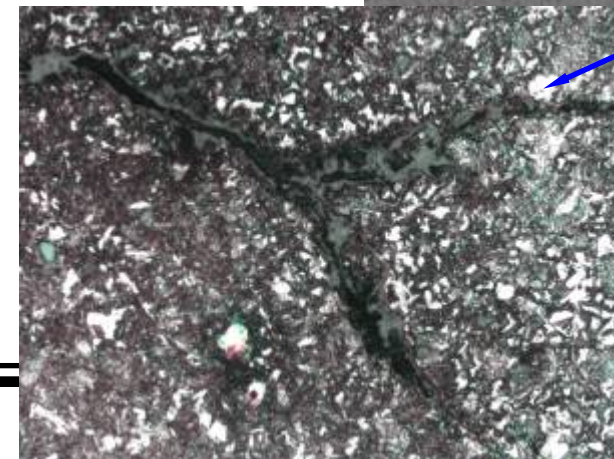
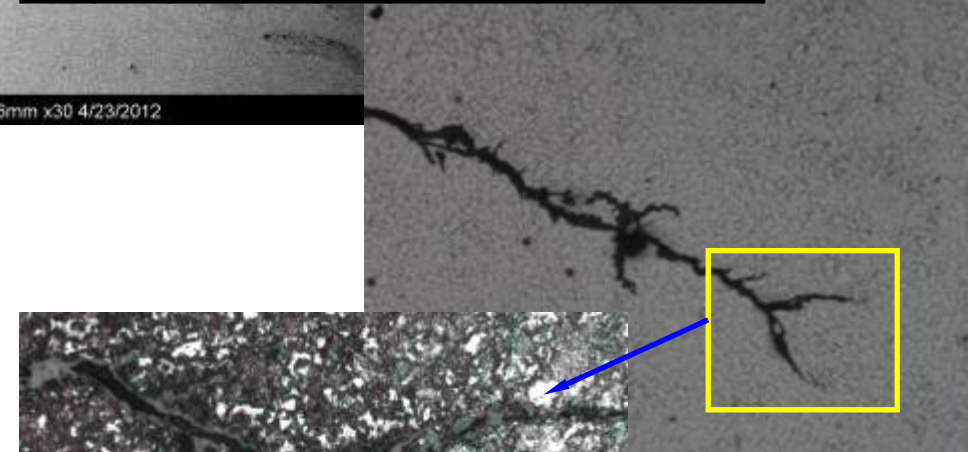
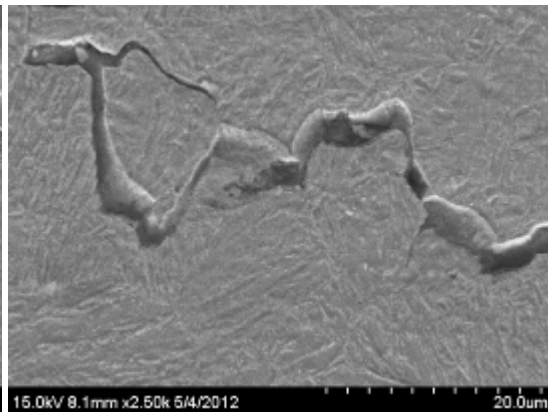
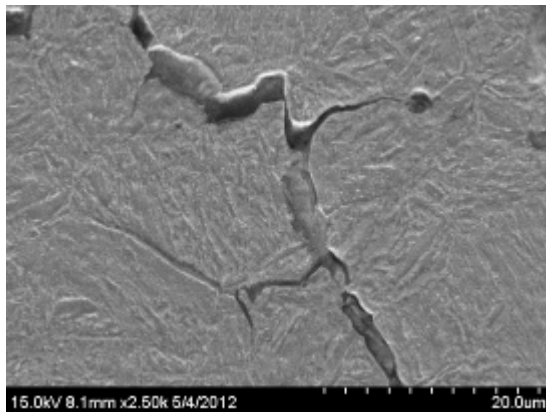
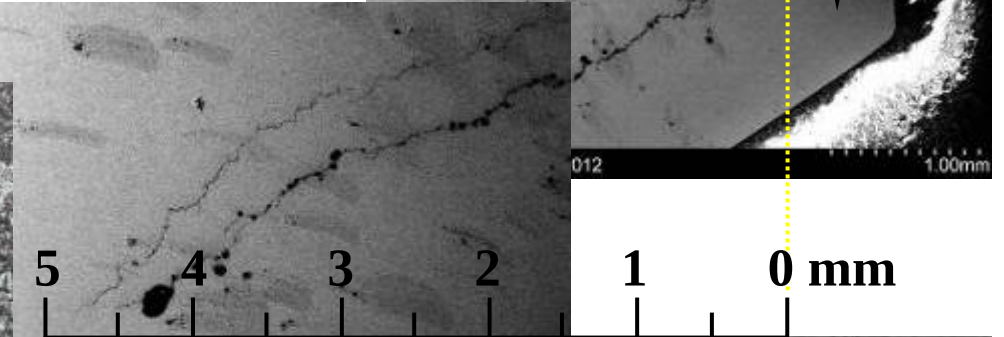
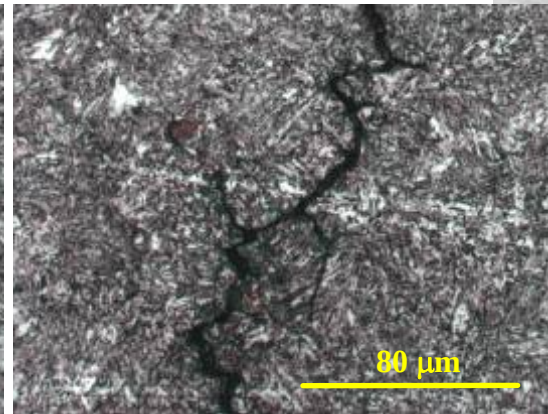
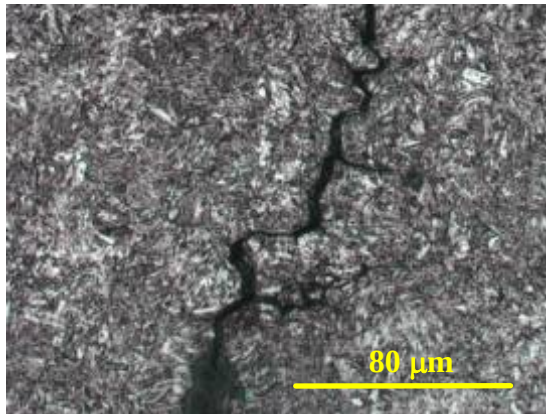
1.00mm

D14

B10

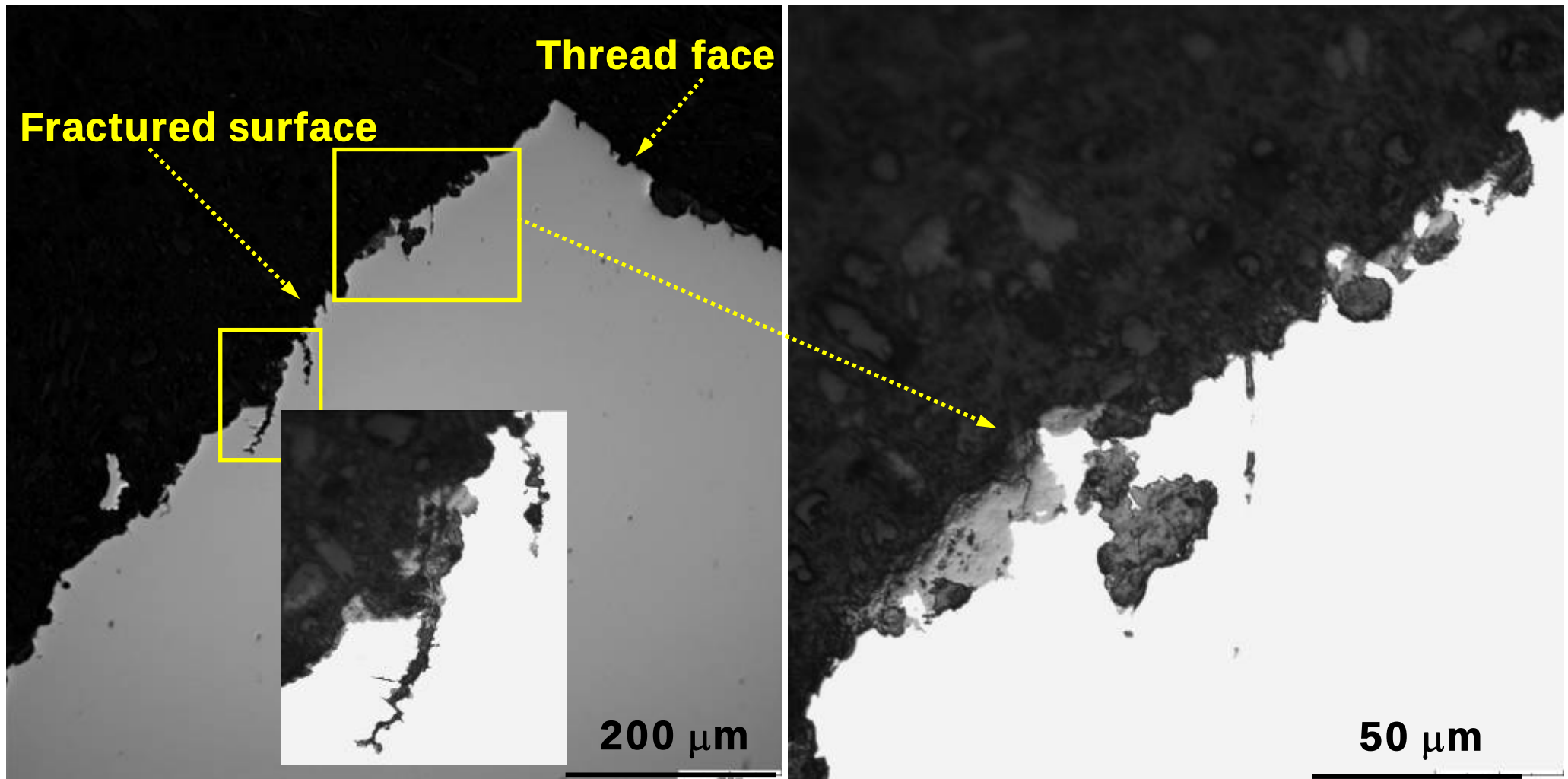
受損螺栓縱剖面分

IG crack + branches

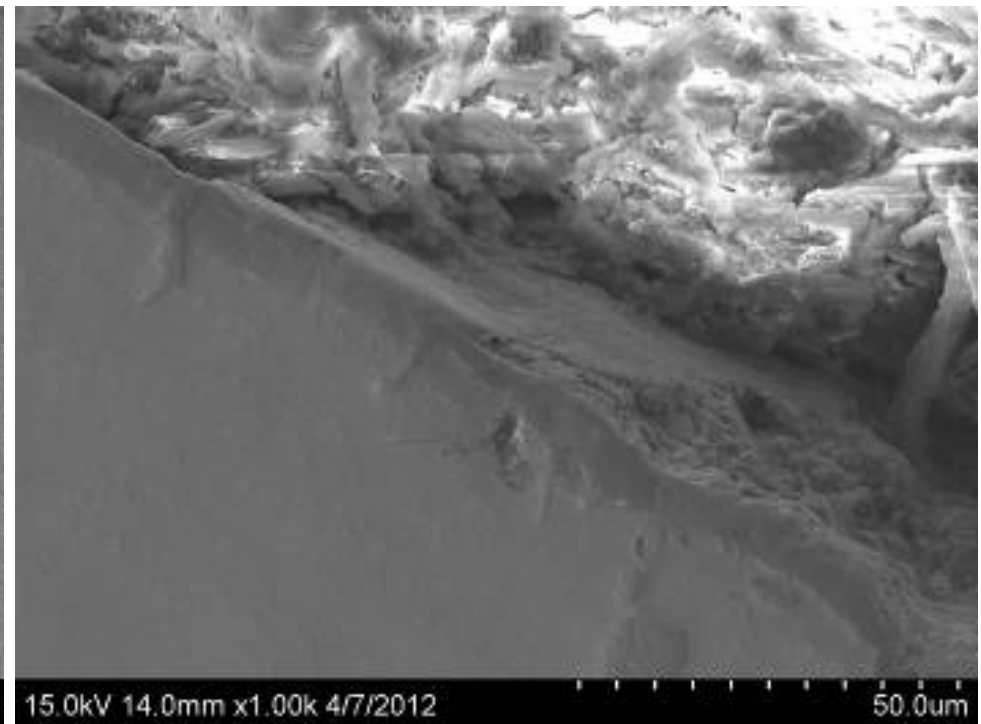
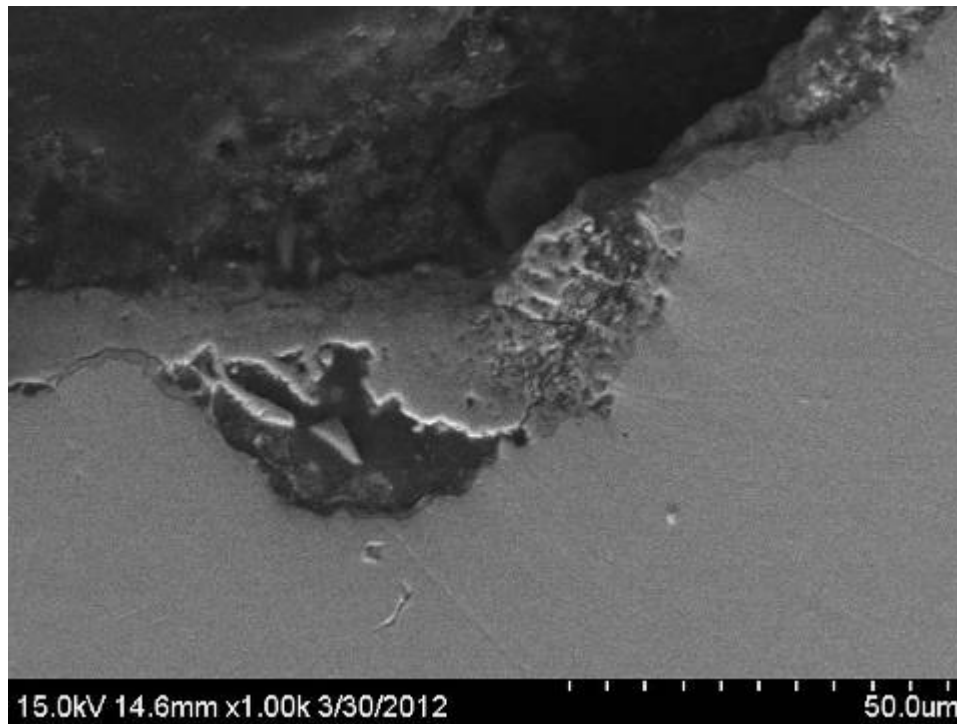


Crack-tip
branching

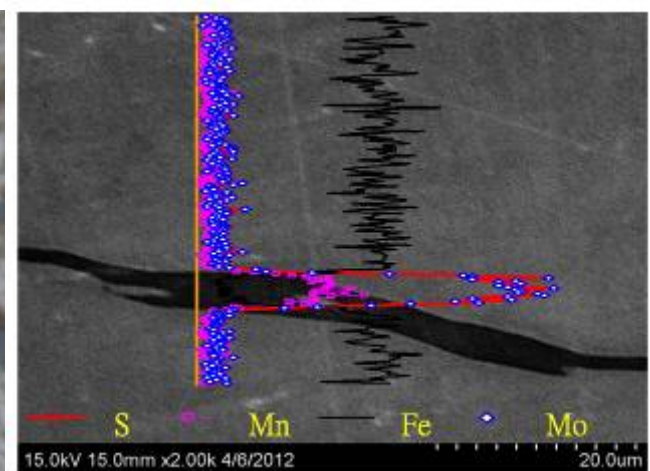
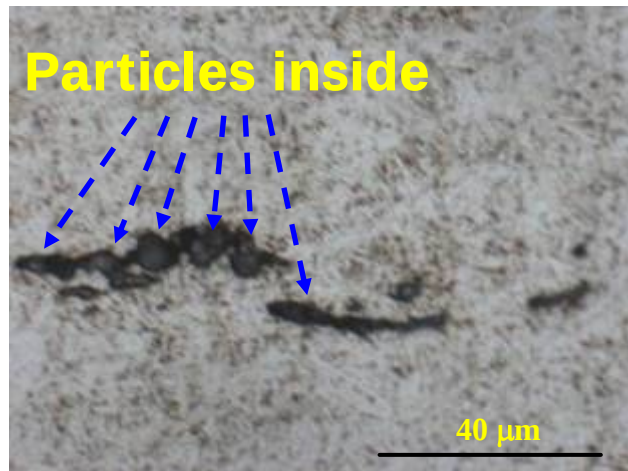
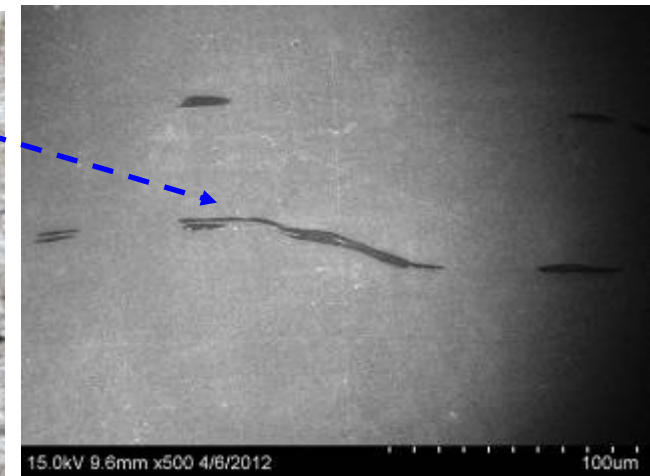
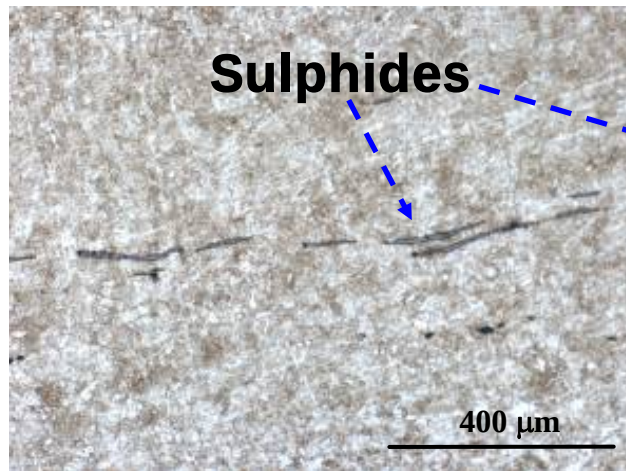
受損螺栓縱剖面分析



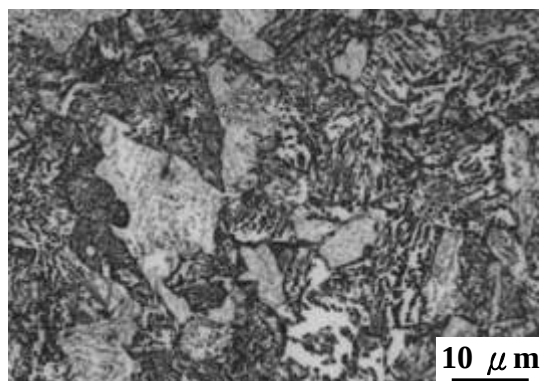
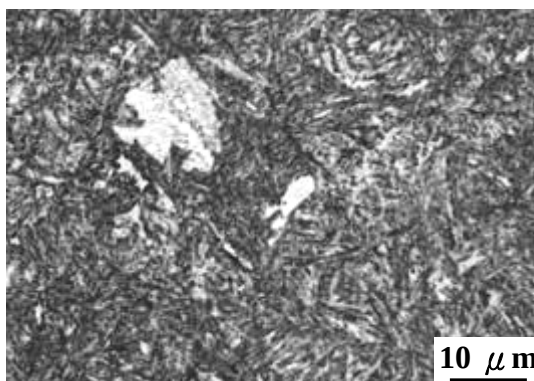
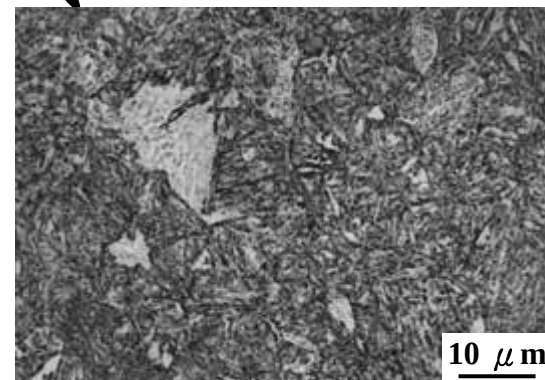
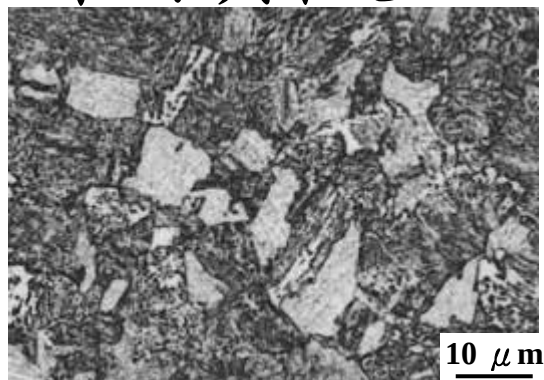
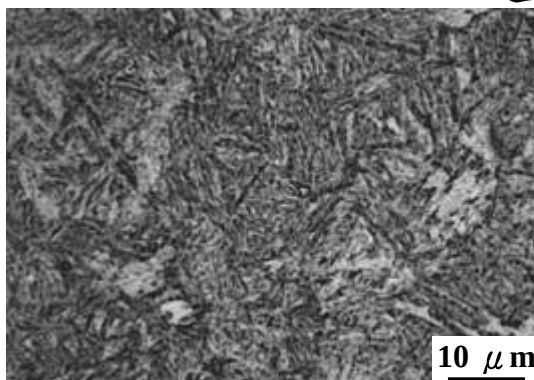
受損螺栓縱剖面分析



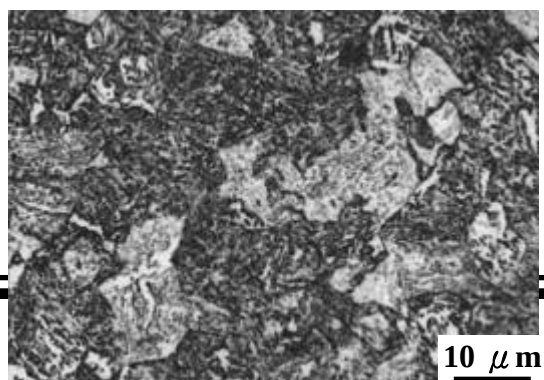
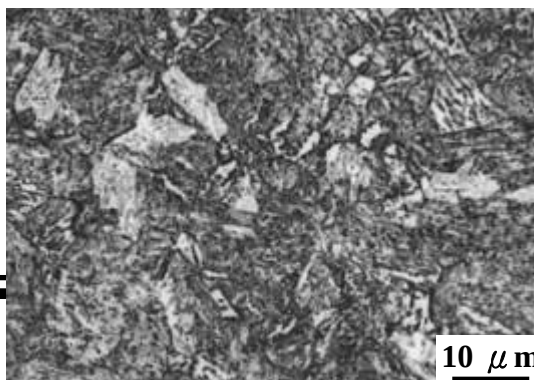
金相顯微組織



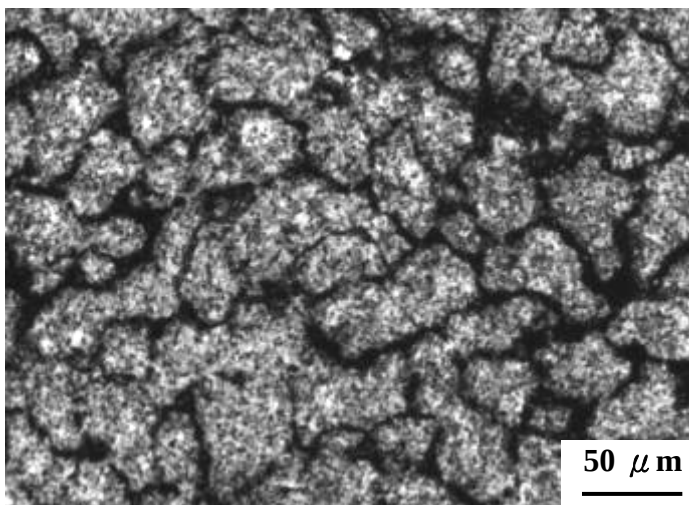
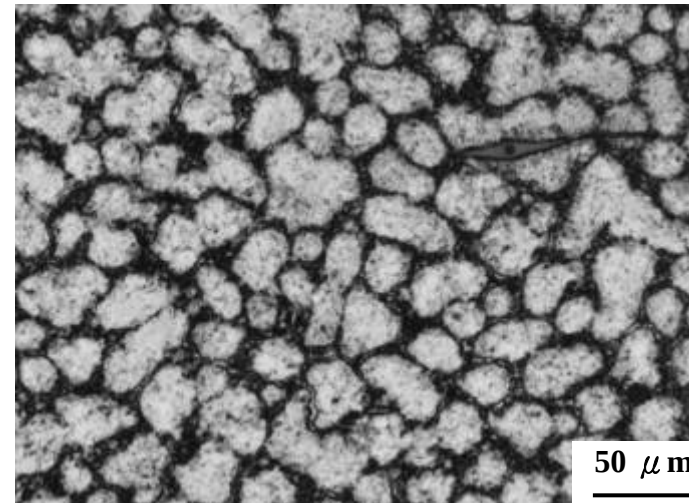
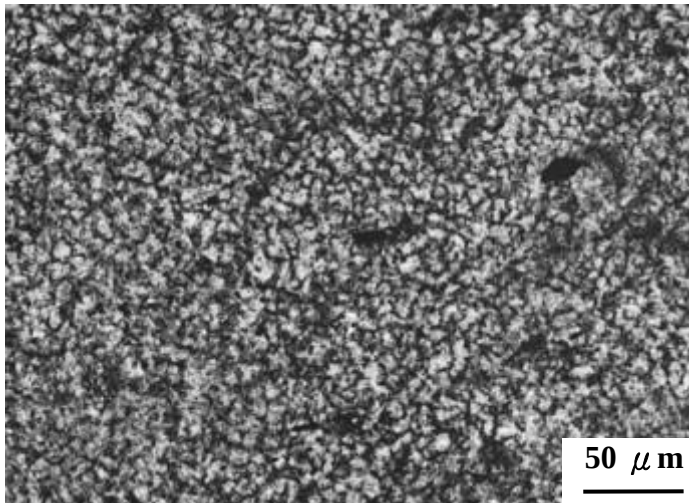
金相顯微組織



A2	B10	D11
C6	B13	
D14	C9	



金相顯微組織



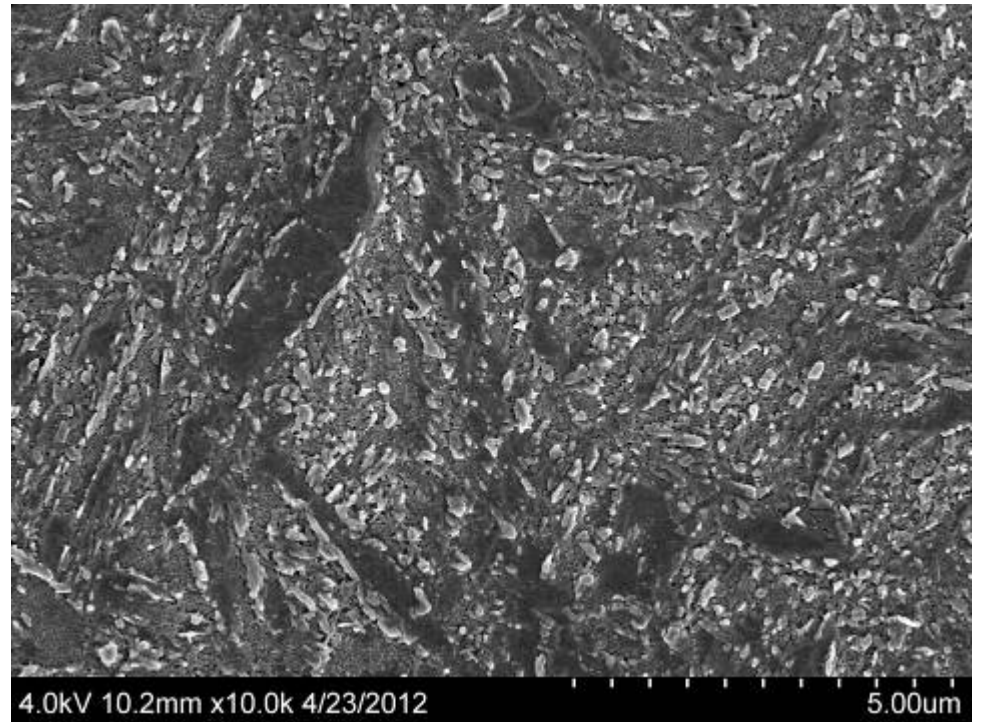
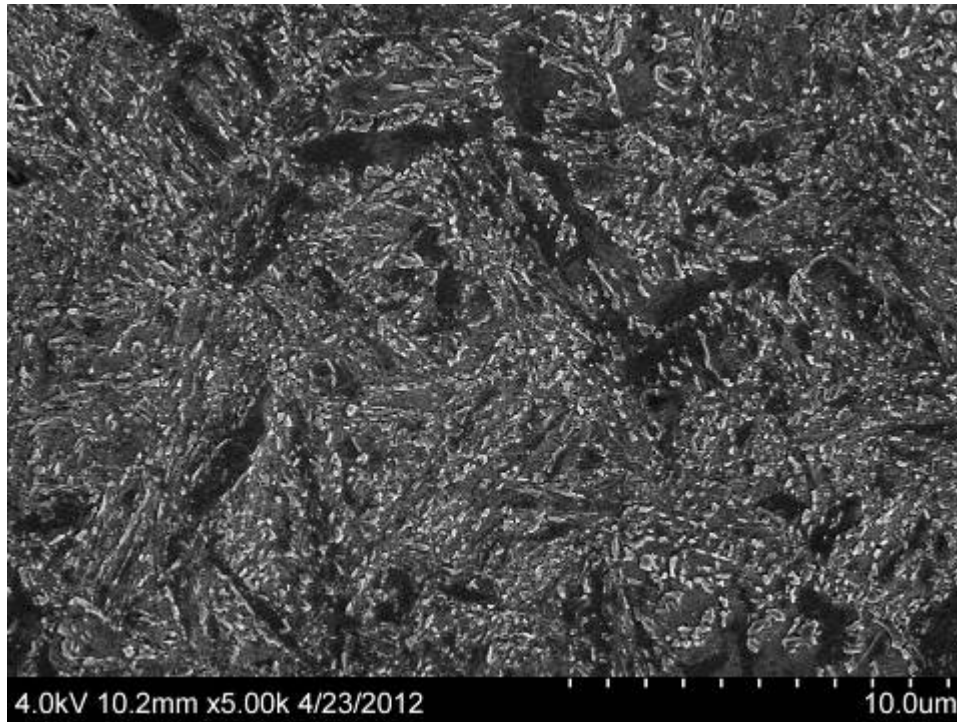
A2

B10

C6

Showing **different** heat-treatment results

金相顯微組織



受損肇因及機制研判



■ 受損肇因分析

- i 開裂角+螺桿開裂+螺牙(面)受損/缺陷 → 安裝不當
- ii 硫化物+微孔+回火微裂紋 → 材料瑕疵
- iii 沿晶龜裂+二次裂紋(分枝)+腐蝕孔+氧化物 → (階段性)腐蝕

{安裝不當 + 材料瑕疵 + 階段性腐蝕} 共同作用，造成螺栓開裂
→ 沿晶龜裂(Intergranular Cracking)

■ 破裂機制研判

- i 裂紋擴展初期可能主導機制：沿晶應力腐蝕龜裂(Intergranular Stress Corrosion Cracking, IGSCC)
- ii 而後轉為疲勞 (Fatigue) 裂紋擴展至終

謝謝
敬請指教