Tool-Life Improvement by Deep-Cryogenic Treatment

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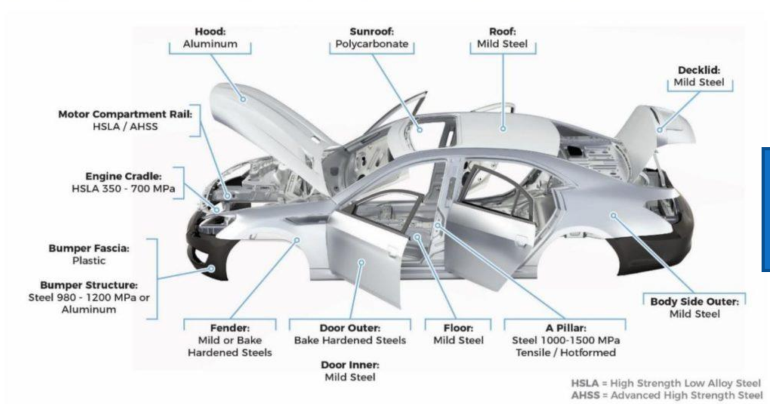
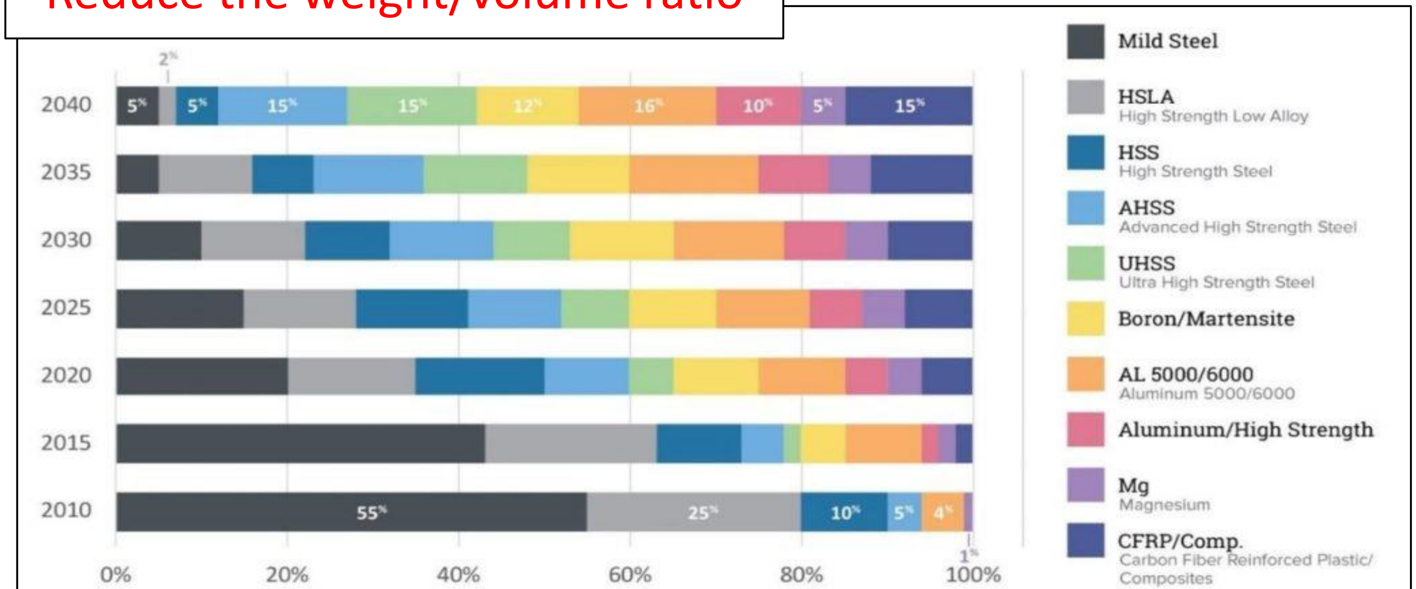
Introduction

Figure 7: Materials Used Most Commonly for Major Vehicle Structure Components in the Current Fleet



Reduce the weight/volume ratio

Increase automotive component efficiency



Picture Source: CAR Research – Automotive Technology Roadmaps (2017)

Introduction

Longer tool life required !!

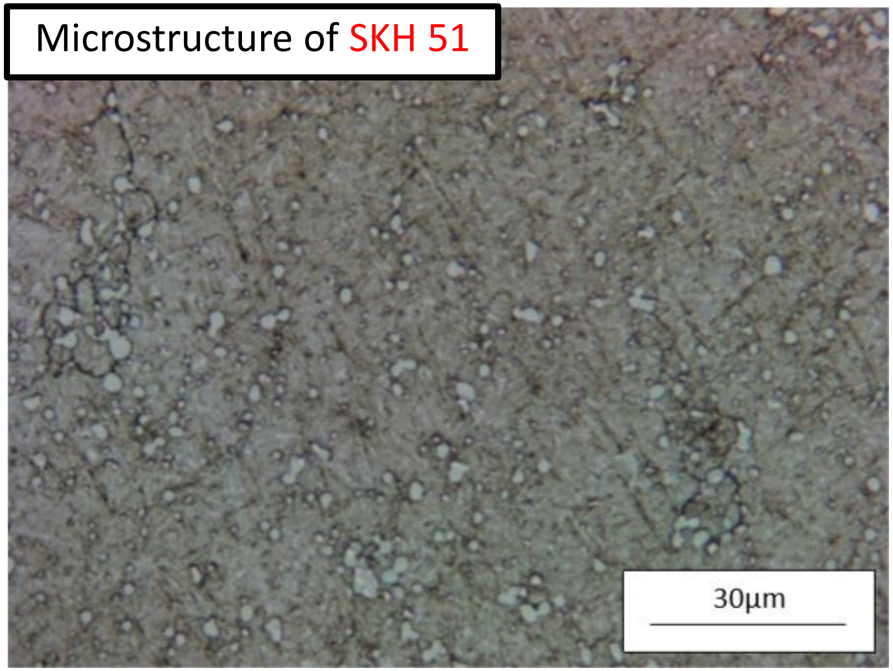
Chemical compositions (wt%)								
	C	Si	Mn	Cr	Mo	Ni	V	Fe
SKH51 (AISI M2)	0.94	0.31	0.29	3.78	4.67	0.26	1.75	79.9
YXR3	0.62	1.36	0.41	4.15	2.55	0.06	1.69	88.7

Microstructure of HSS

Chemical compositions of SKH51 (%wt.)

C	Si	Mn	Cr	W	Mo	V	Co
0.9	0.3	0.4	4.2	6.5	5.0	2.0	-

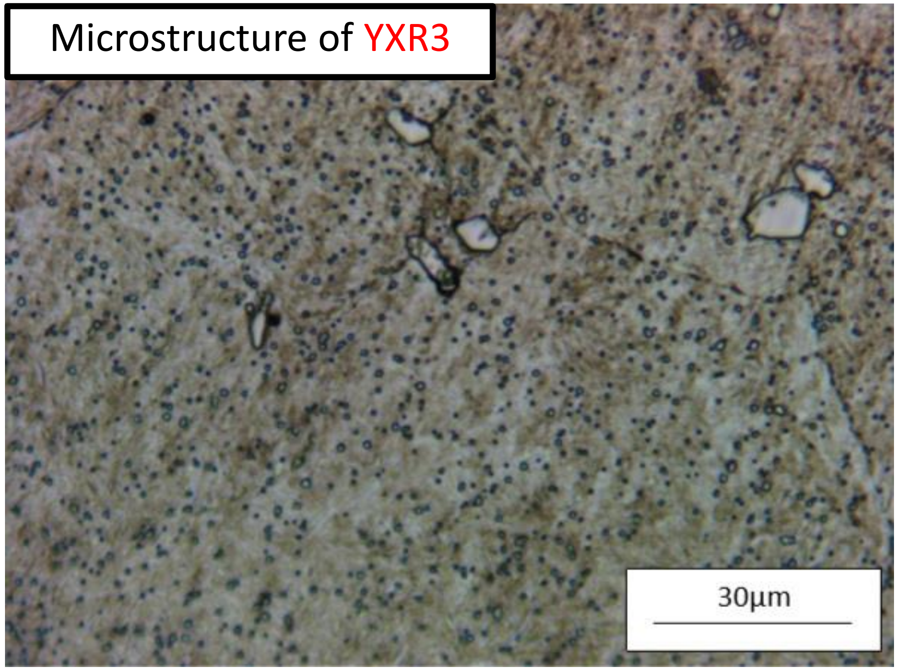
Microstructure of SKH 51



Chemical compositions of YXR3 (%wt.)

C	Si	Mn	Cr	W	Mo	V	Co
0.6	1.5	0.4	4.3	-	2.9	1.8	-

Microstructure of YXR3



- The amount of carbide in YXR3 is higher than SKH51
- The smaller carbides (dia.1.38 um) are randomly distributed along YXR3 compare to SKH51(dia. 2.19 um)

Wear of Tool Steels

Archard's equation

$$\dot{w} = k_0 \frac{P}{H}$$

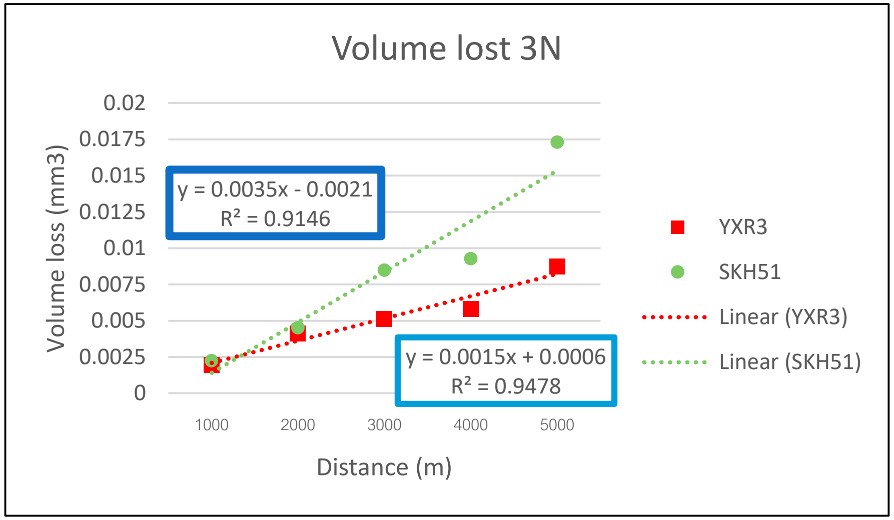
Modification of Archard's equation

$$\dot{w} = k \frac{P}{H} = k_0 \frac{\varepsilon_p \cdot P}{\varepsilon_c \cdot H} = k_0 \frac{\alpha \, P^{\frac{1}{2}} \, m^2 \, E \, \sigma_y \, P}{\beta \, H^{\frac{1}{2}} \, K_{IC}^2 \, H}$$

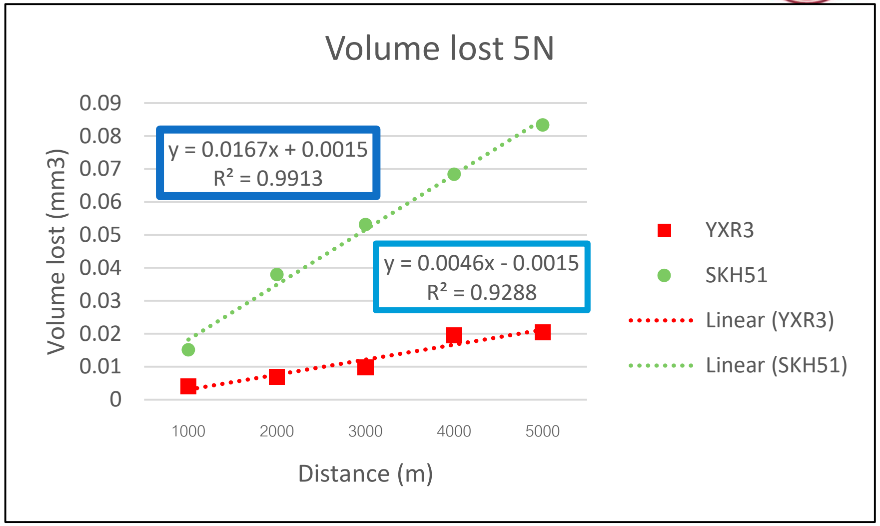
The wear coefficient k_0, is defined as the probability that decohesion of a certain volume of matter occurs at a given area

This can be confirmed that wear rate of materials is controlled not only Hardness but Toughness

Wear testing Results

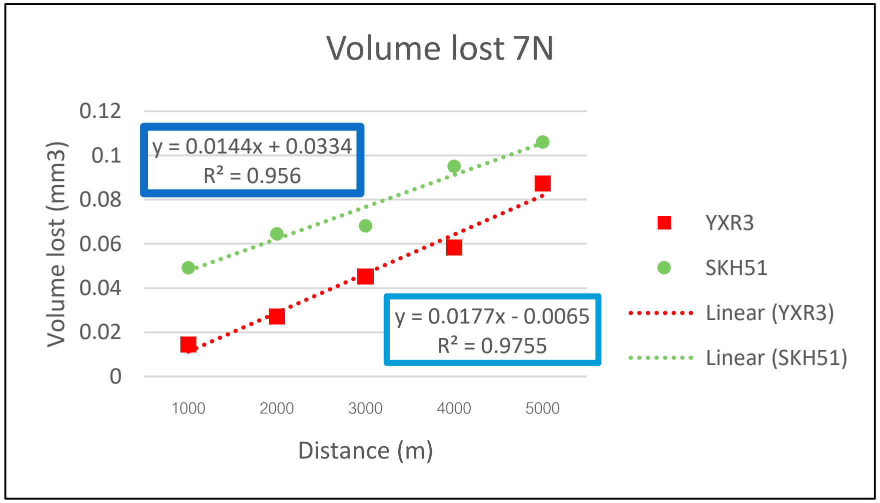


Wear volume loss of high-speed steel in 3N load



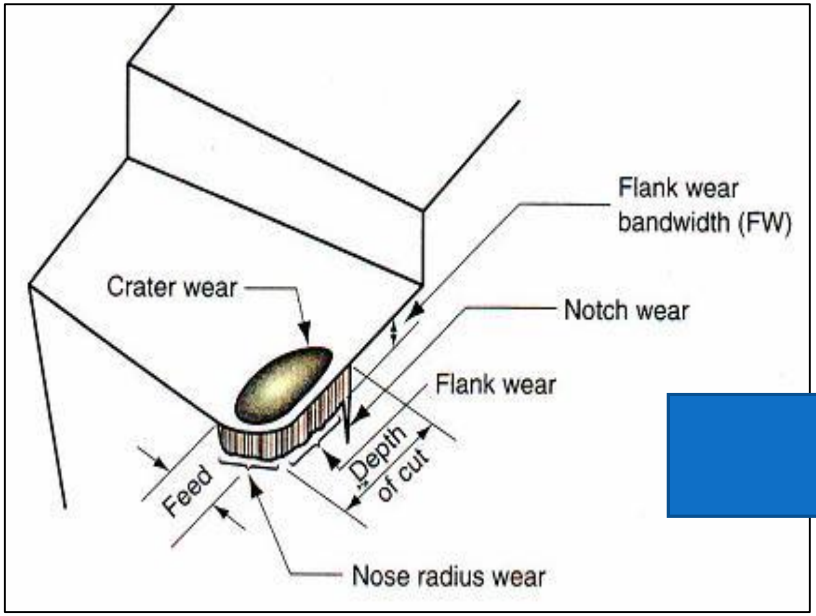
Wear volume loss of high-speed steel in 5N load

Testing Parameters	
Load	3,5,7 N
Speed (Motor speed)	500 rpm
Sliding distance	5000 m
Ball Diameter	6 mm
Ball Material	WC-Co

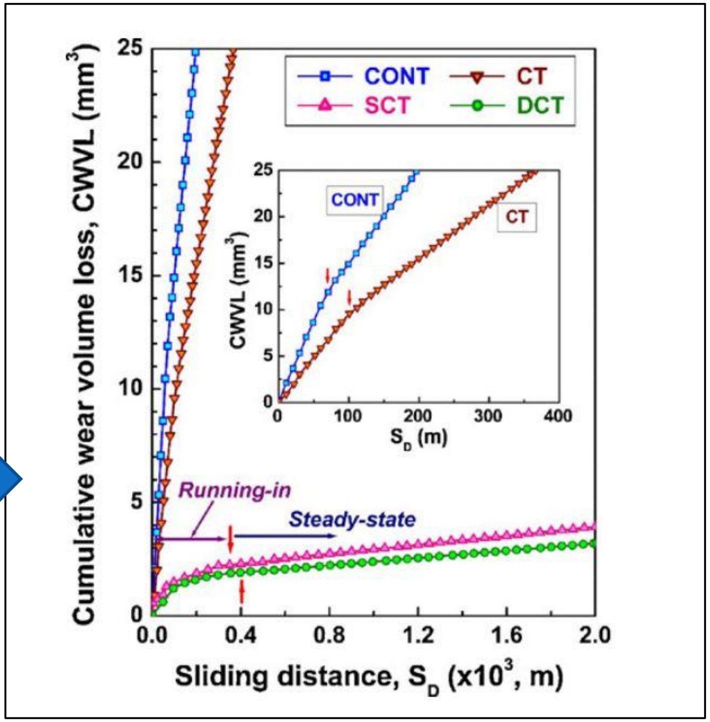


Wear volume loss of high-speed steel in 7N load

Tool Life Improvement by DCT



Wear of cutting tools [1]

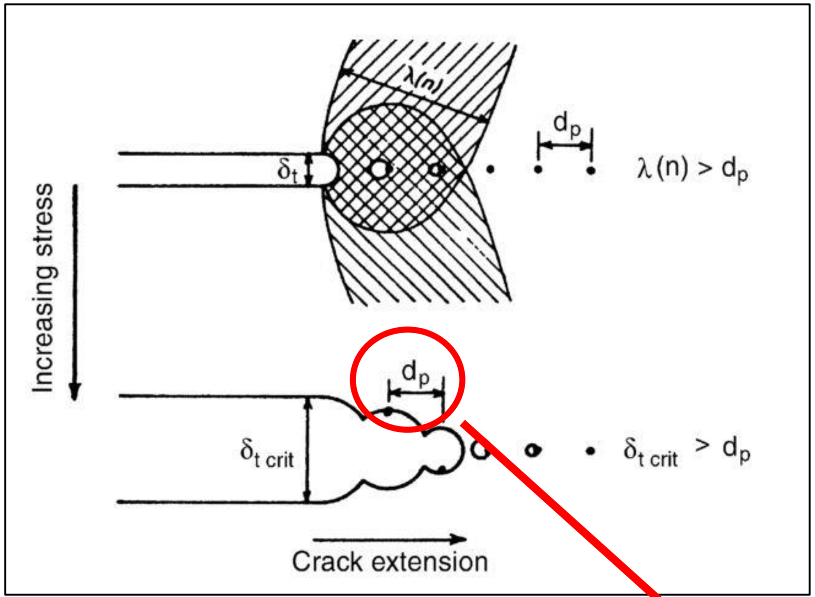


Plot of cumulative wear volume loss (CWVL) versus sliding distance (SD) for differently treated specimens tested at sliding velocity of 1.25ms−1, [2]

The improvement in wear resistance is as a result of five-main phenomena:

1. The reduction or elimination of retained austenite (γR)
2. Increased precipitation
3. Refinement of secondary carbide
4. Homogeneous the microstructure
5. Augmentation of volume fraction of carbide.

Carbide Effect on Fracture Toughness



The formation of microvoids next to particles (inclusions, precipitates) within the region of intense plastic strain at the crack tip

Hahn and Rosenfield's strain criterion

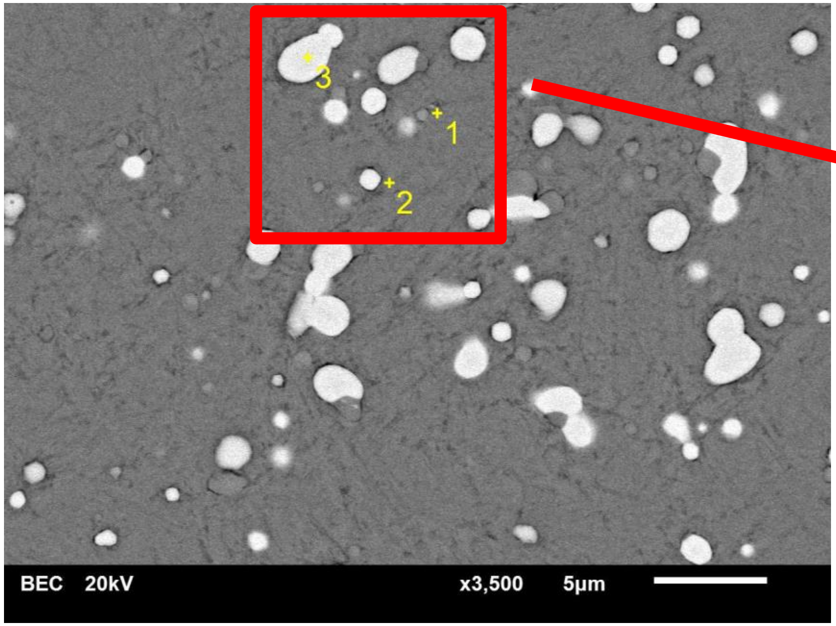
$$K_{IC} \equiv \sqrt{J_{IC} \times E} = \sqrt{E \cdot \sigma_{YS} \cdot \varepsilon_f \cdot l_o}$$

J_{IC} is the critical J integral,
E is Young's modulus in plane stress,
σ_{YS} is the yield stress,
ε_f is the equivalent critical local fracture strain,
l_o is the characteristic microstructural distance for fracture.

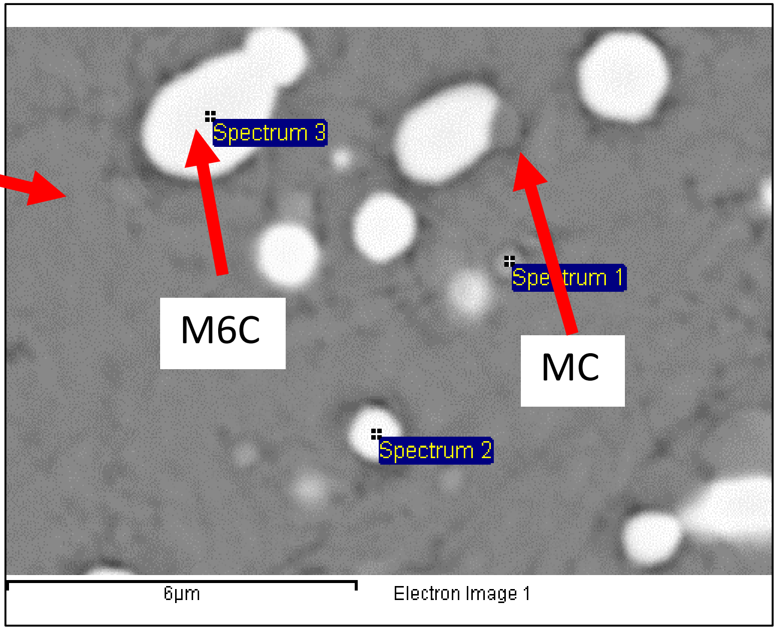
Many literatures reported that the fracture toughness decrease when decreasing of the distance between these particles described as $K_{IC} \propto f^{-1/6}$

$$K_{IC} = \sqrt{E \cdot \sigma_{YS} \cdot \varepsilon_f \cdot d_p} \cdot f^{-1/6}$$

SEM & EDS results of SKH51



SEM micrograph of Microstructure of SKH51 before cryogenic treatment



Microstructure of SKH51 before cryogenic treatment

EDS results of SKH51 (%wt.)

Spectrum	C	O	V	Cr	Fe	Mo	W	Total
Spectrum 1	12.53		14.20	3.86	45.12	10.55	13.74	100.00
Spectrum 2	5.67	2.29	2.22	3.47	40.70	17.57	28.08	100.00
Spectrum 3	4.95	1.71	2.87	3.00	28.94	23.71	34.80	100.00

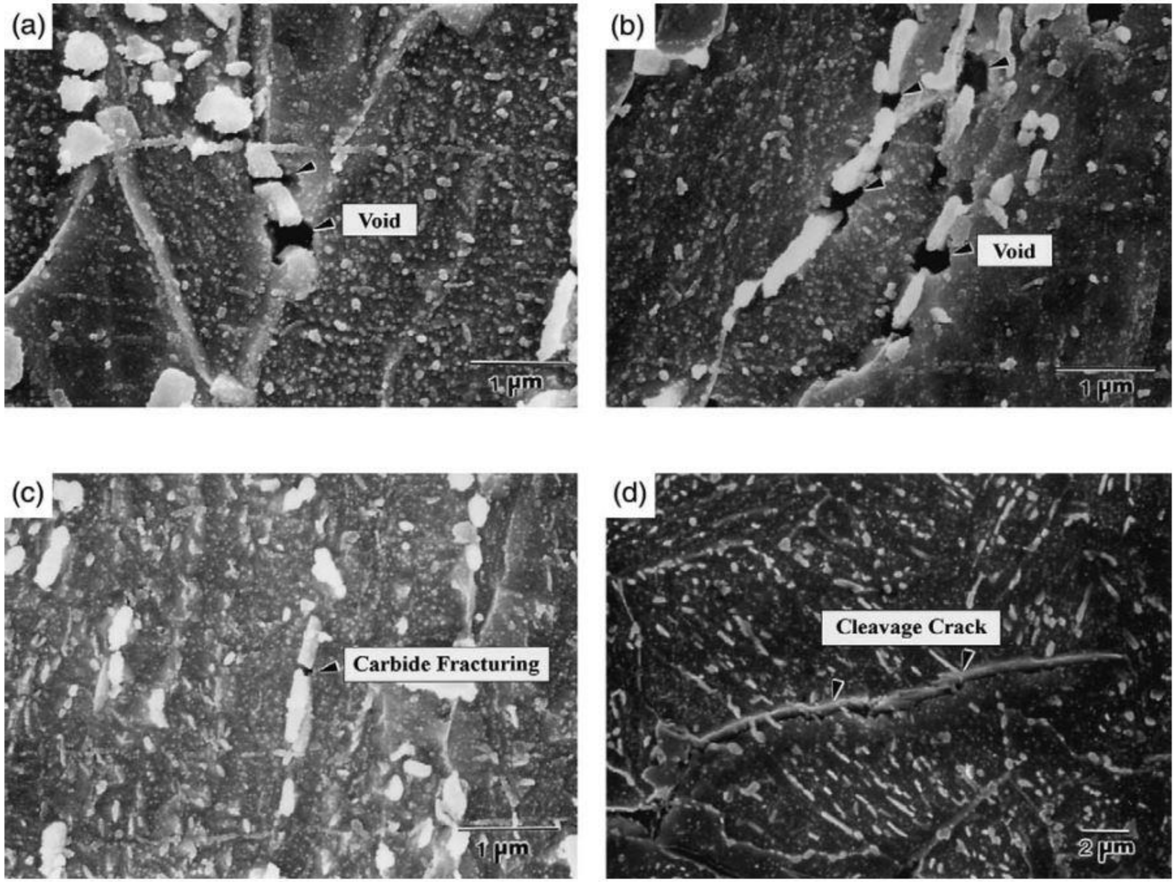
MC is Vanadium Carbide (VC)

M_6C is $(Fe,Mo)_3W_3C$

Chemical compositions of SKH51 (%wt.)

C	Si	Mn	Cr	W	Mo	V	Co
0.94	0.31	0.29	3.78	5.85	4.67	1.75	0.55

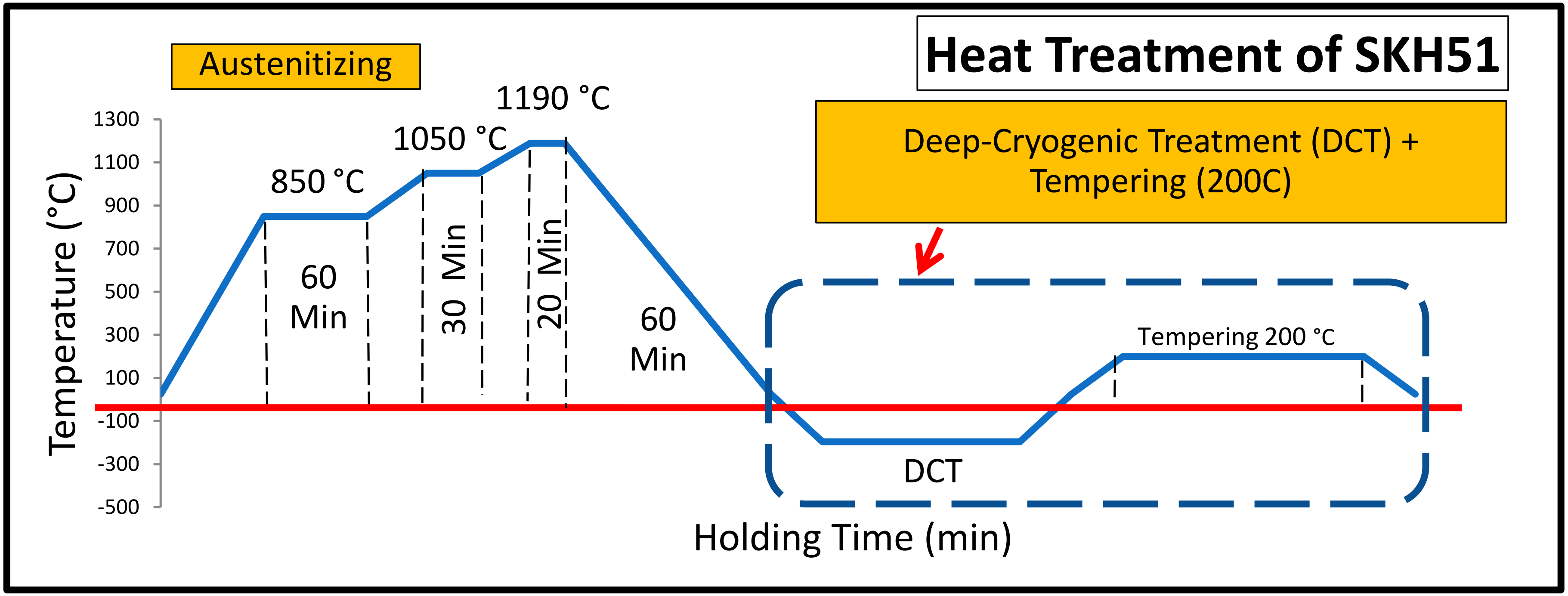
Carbide Types Effect



SEM micrographs of the cross-sectioned area beneath the fracture surface of the circumferentially notched tensile specimen tested (a) and (b) at –75 C and (c) and (d) at –140 C, showing the cracking and void initiation at carbides. The tensile axis is vertical for the micrographs. Nital etched. [1]

[1] S. Lee, S. Kim, B. Hwang, B. S. Lee, C. G. Lee,. "Effect of carbide distribution on the fracture toughness in the transition temperature region of an SA 508 steel",. Acta Materialia 50 (2002) 4755–4762

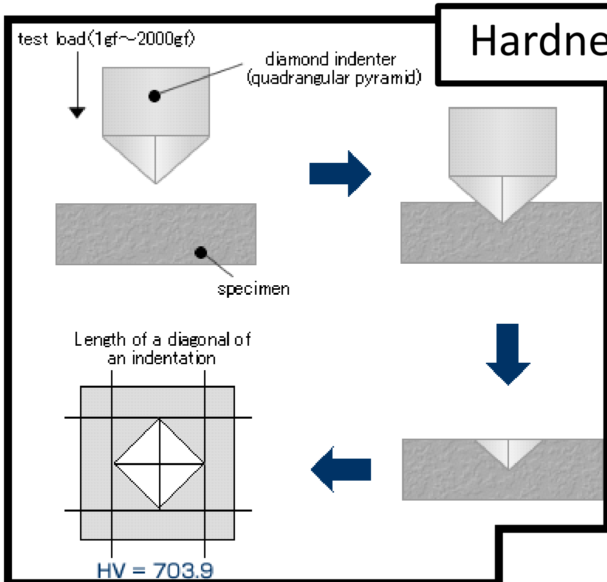
Heat Treatment Profile of DCT Analysis



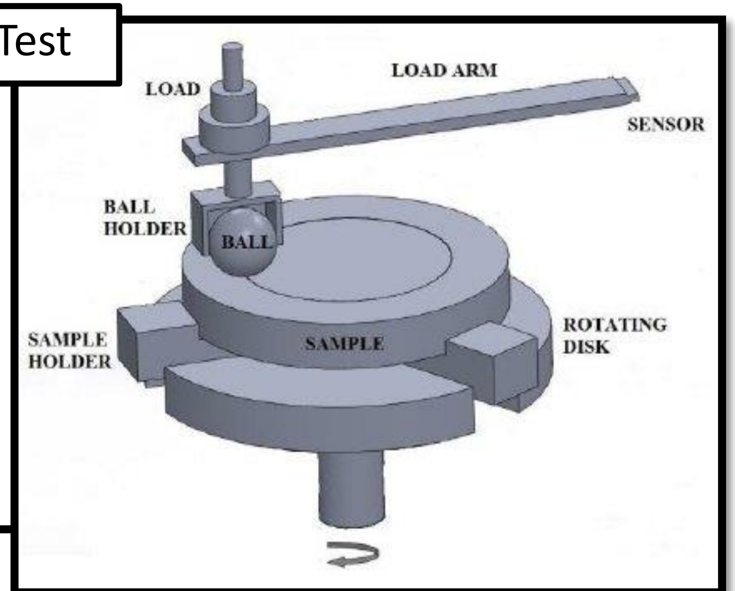
DCT condition investigated in this research				
No.	Name	DCT Temperature (˚C)	DCT Holding time (Hr)	Tempering temperature (˚C)
1	-140x12_T200	-140	12	200
2	-200x12_T200	-200	12	200
3	-140x36_T200	-140	36	200
4	-200x36_T200	-200	36	200

Mechanical Testing

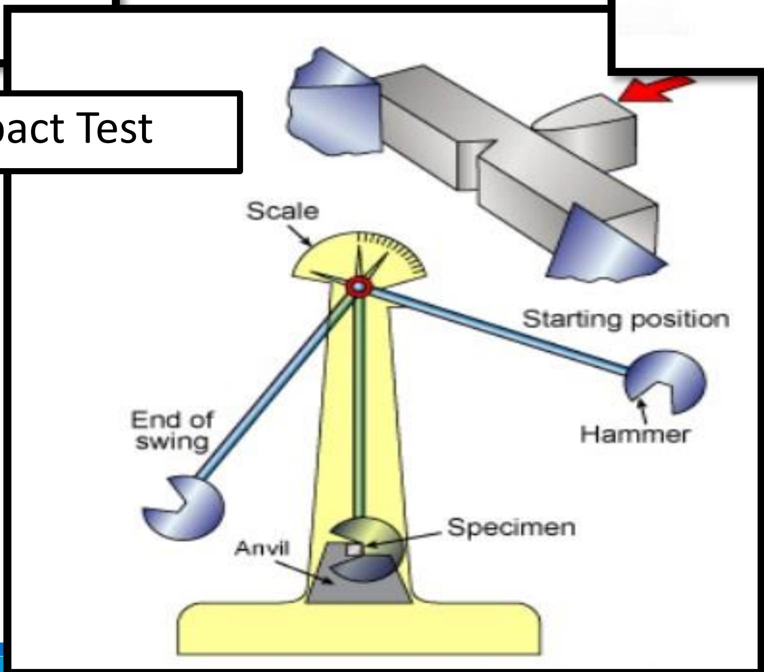
Hardness Test



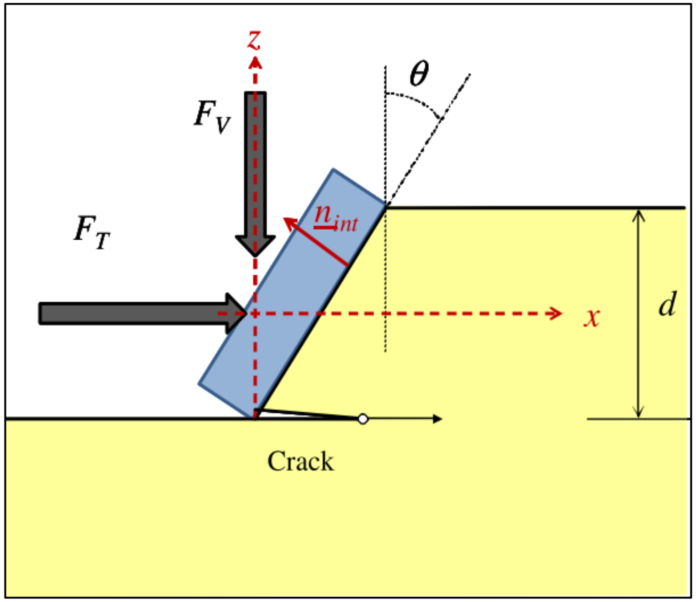
Ball on Disk Test



Charpy Impact Test



Scratch test for K1C Determination

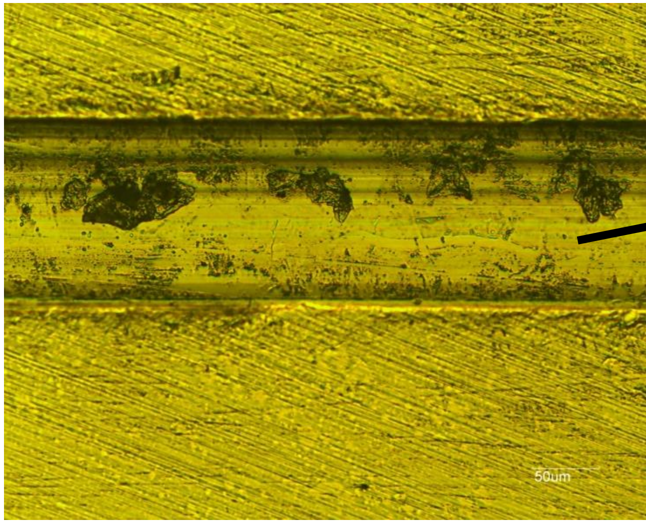


$$J = \oint \left(\psi n_x - T(\underline{n}) \cdot \frac{\partial \underline{\xi}}{\partial x} \right) ds = - \int_{z=-d/2}^{z=d/2} \left(\psi + \frac{1}{\cos\theta} T(\underline{n}_{int}) \cdot \frac{\partial \underline{\xi}}{\partial x} \right) dz$$

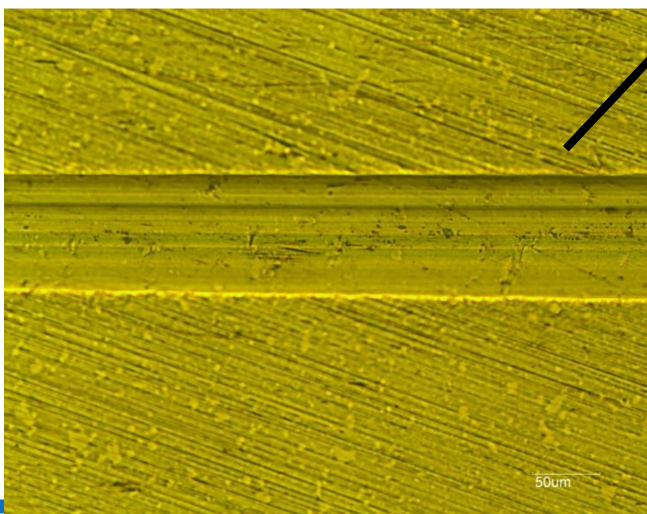
Free energy contribution

Displacement-gradient contribution

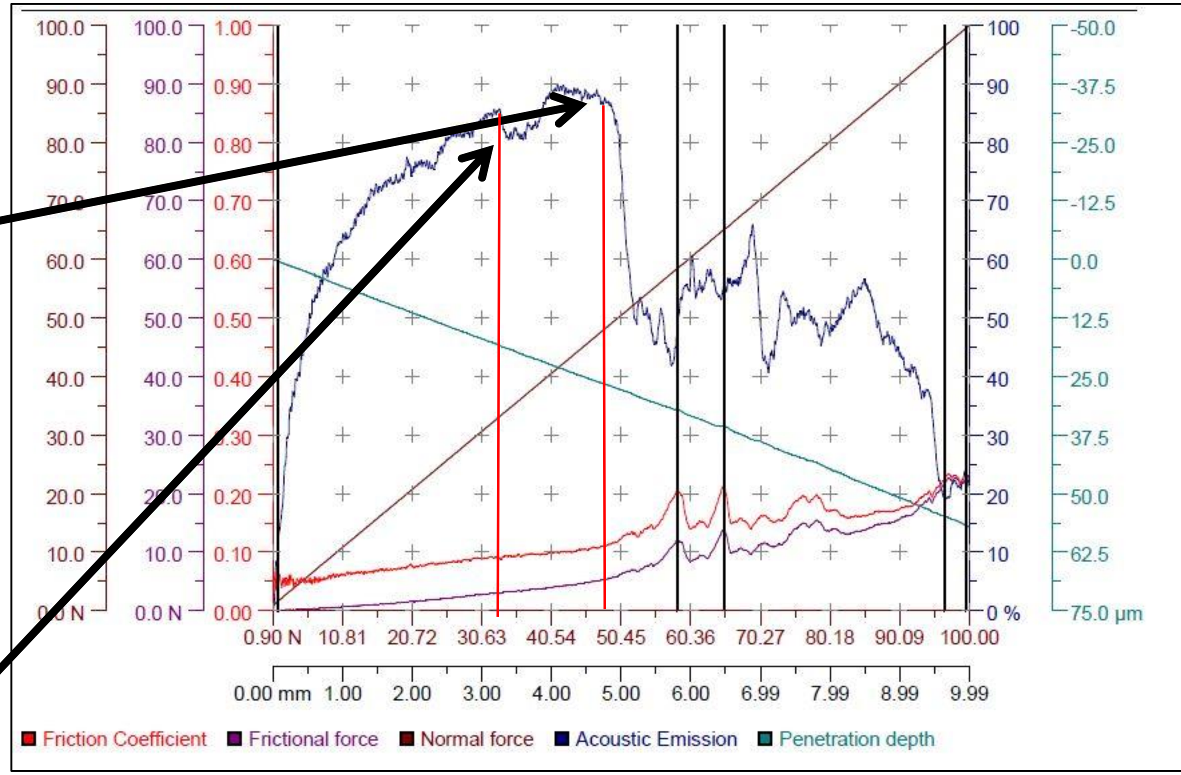
Ft and Penetration Depth Selected Based on Acoustic Emission Signal



Crack results from Scratch test at AE Sudden change

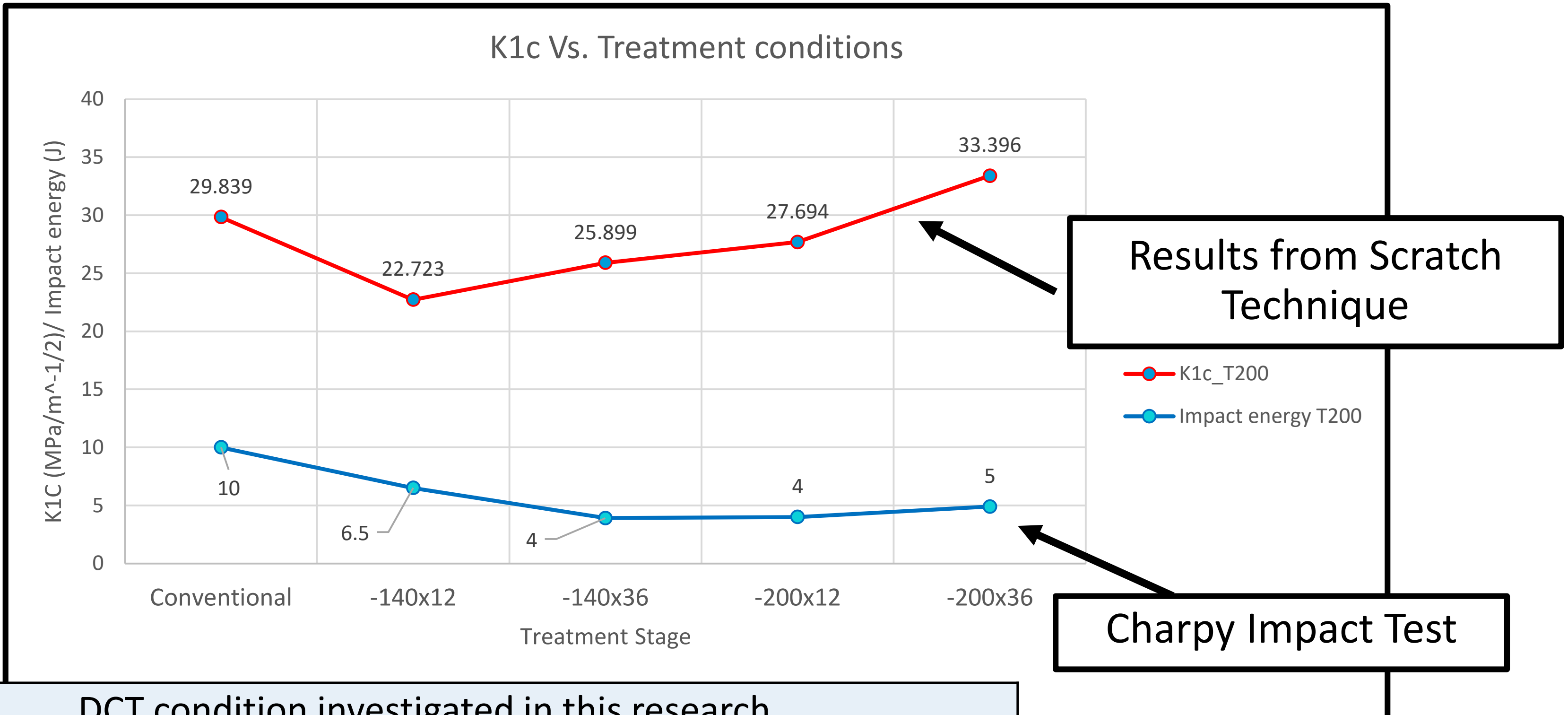


Scratch Line



Results from the Scratch test

Scratch Testing Vs Charpy Impact Test



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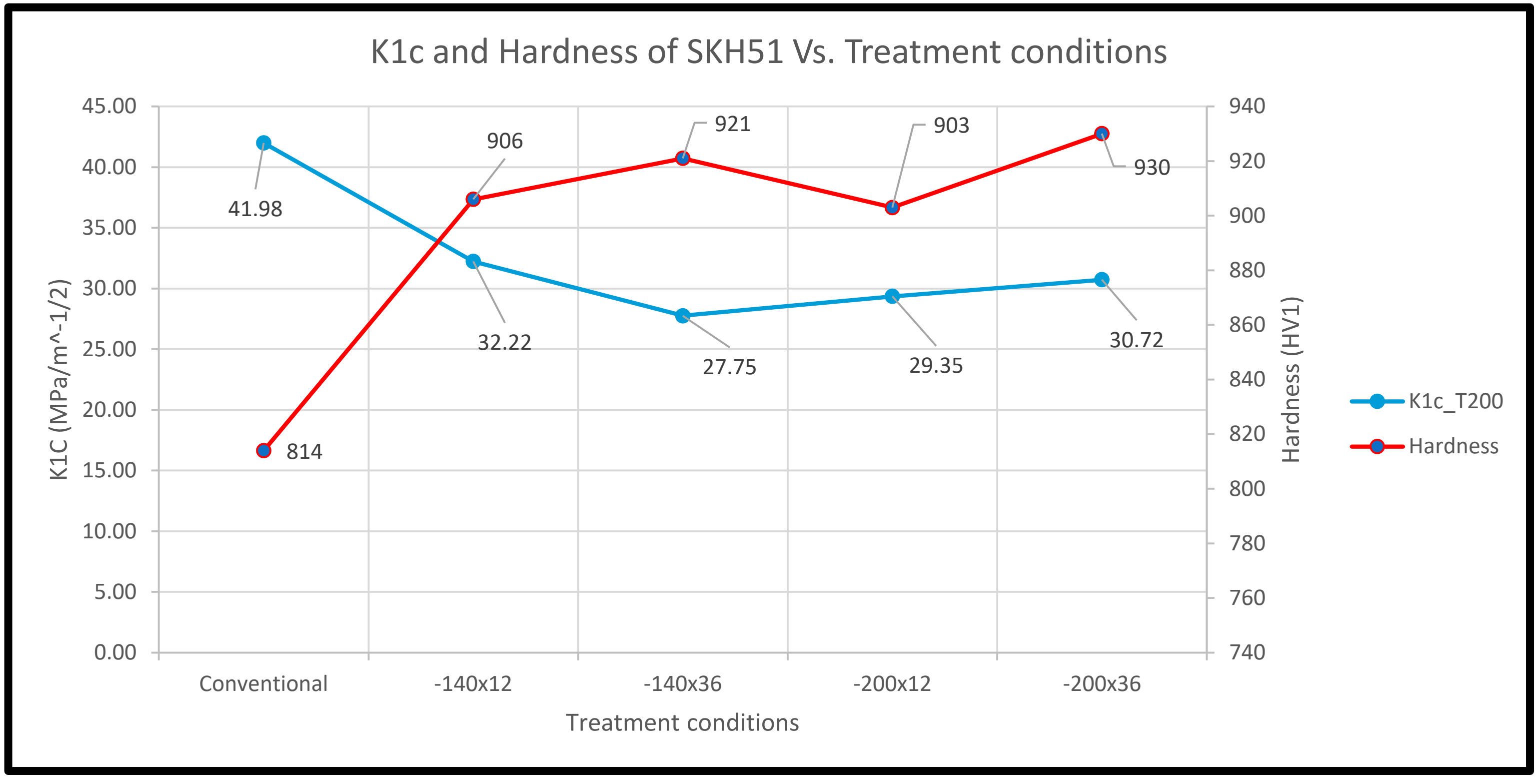
No.	Name	DCT Temperature (˚C)	DCT Holding time (Hr)	Tempering temperature (˚C)
1	-140x12_T200	-140	12	200
2	-200x12_T200	-200	12	200
3	-140x36_T200	-140	36	200
4	-200x36_T200	-200	36	200

Chemical compositions (wt%)								
	C	Si	Mn	Cr	Mo	Ni	V	Fe
YXR3	0.62	1.36	0.41	4.15	2.55	0.06	1.69	88.7

DCT Parameters Effect on SKH51



<u>Hardness</u>

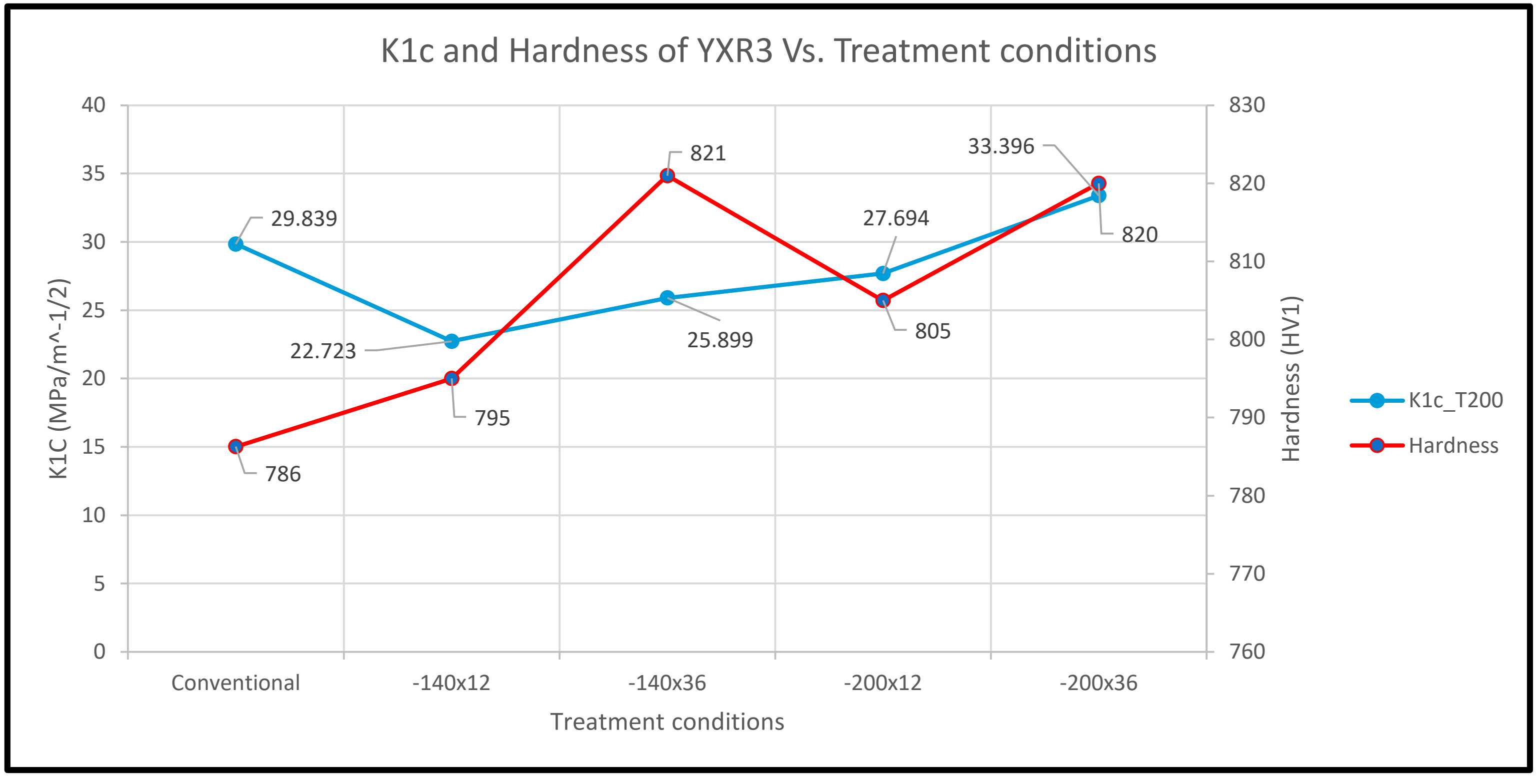
- SKH51➔ 814 HV ➔ 930 HV (↑ 15% Increase)

<u>Toughness</u>

- SKH51➔ 42 ➔ 30 Mpa/m^-1/2 (↓ 30% Decrease)

Chemical compositions (wt%)								
	C	Si	Mn	Cr	Mo	Ni	V	Fe
SKH51 (AISI M2)	0.94	0.31	0.29	3.78	4.67	0.26	1.75	79.9

DCT Parameters Effect on YXR3



Hardness

- YXR3➔ 786 HV ➔ 820 HV (↑ 15% increase)

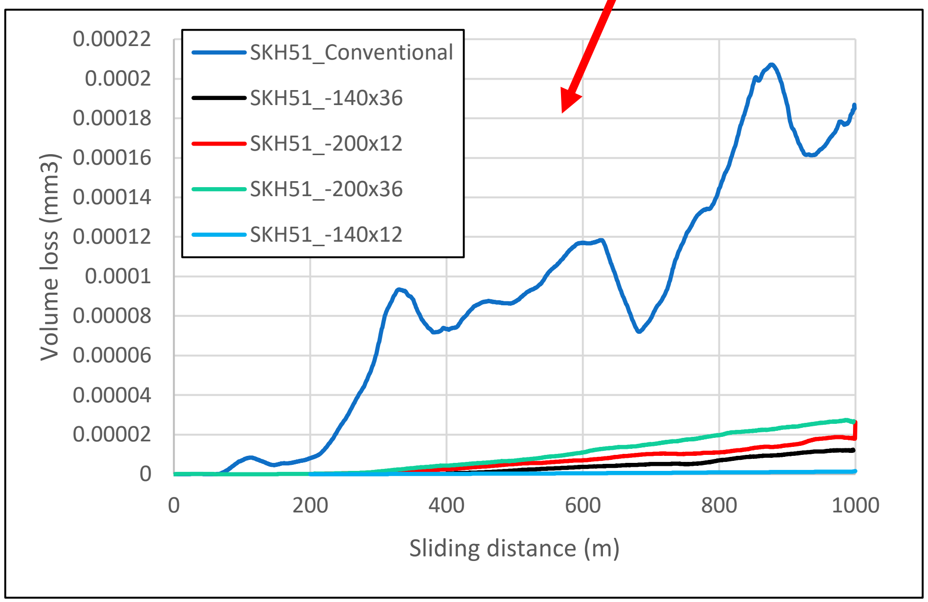
Toughness

- SKH51➔ 30 ➔ 33 Mpa/m^-1/2 (↑ 10% increase)

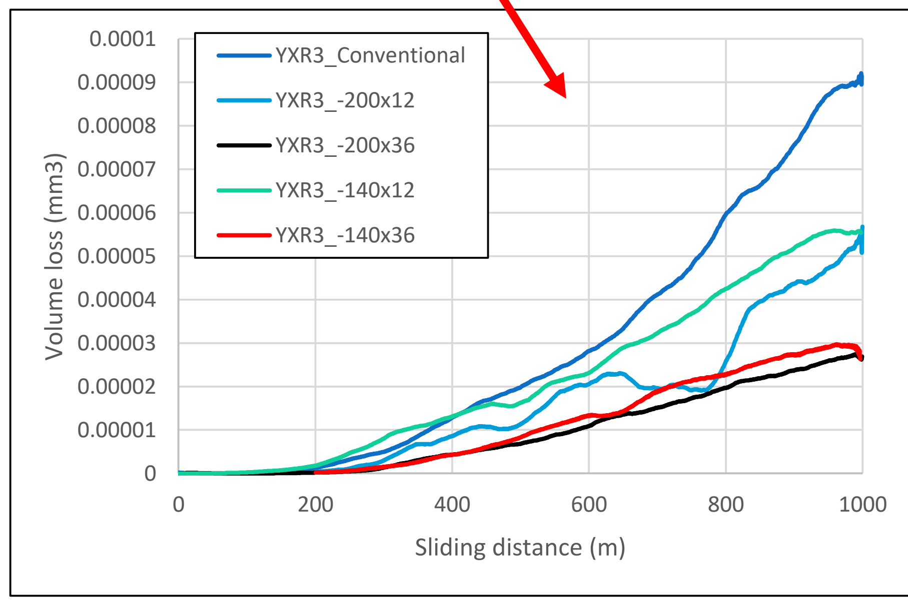
Chemical compositions (wt%)								
	C	Si	Mn	Cr	Mo	Ni	V	Fe
YXR3	0.62	1.36	0.41	4.15	2.55	0.06	1.69	88.7

Wear Testing Results

	SKH51					YXR3				
	Conventional	-200 °C		-140 °C		Conventional	-200 °C		-140 °C	
		12 hr	36 hr	12 hr	36 hr		12 hr	36 hr	12 hr	36 hr
Wear Rete (mm3/m) $(x10^{-8})$	11.7	4.00	4.00	3.67	3.00	23.3	9.00	3.33	12.30	4.67
Improvement Percentage (%)	-	66 %	66 %	69 %	74 %	-	61 %	86 %	47 %	80 %

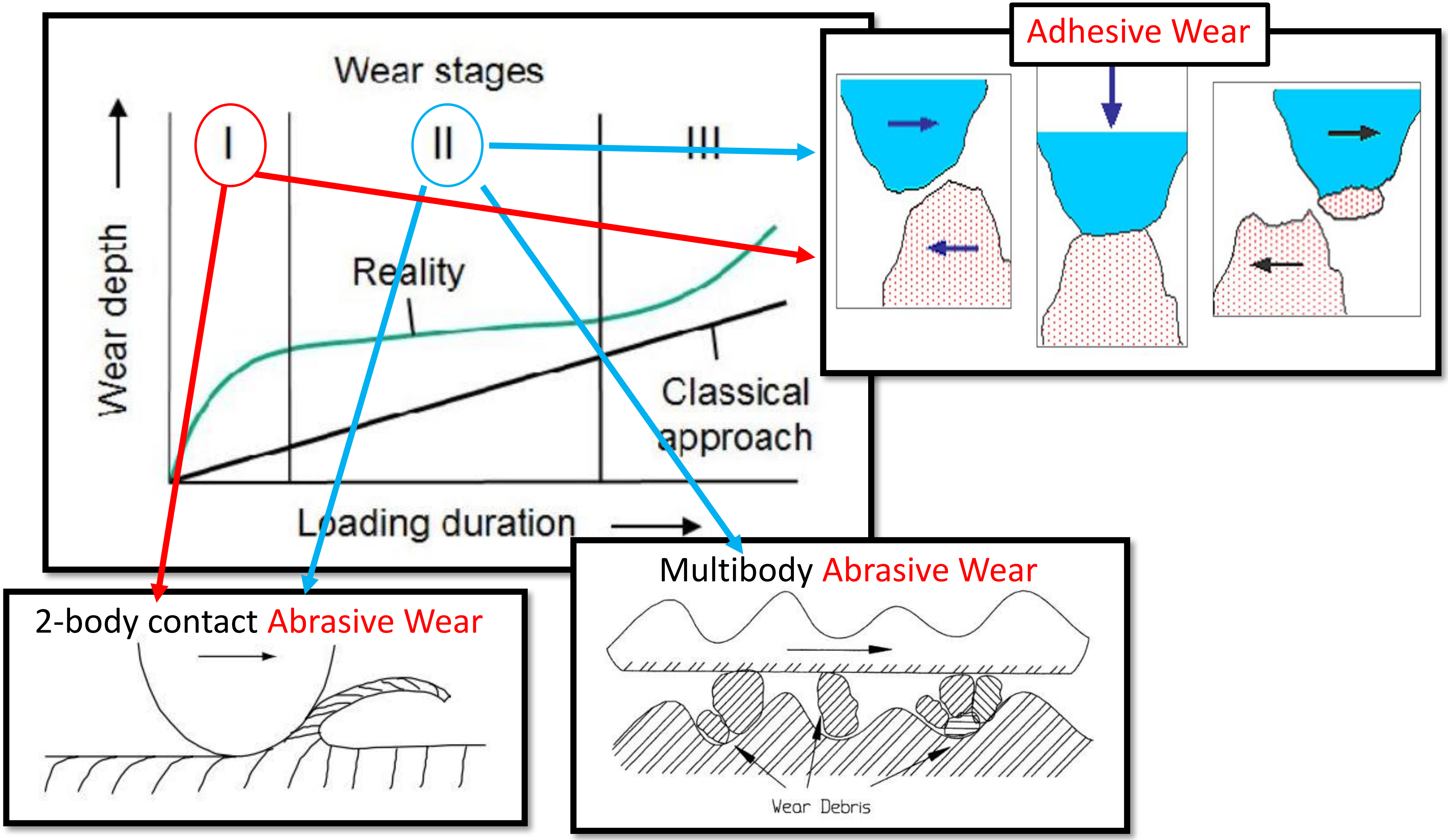


Volume loss of SKH51 under different DCT conditions



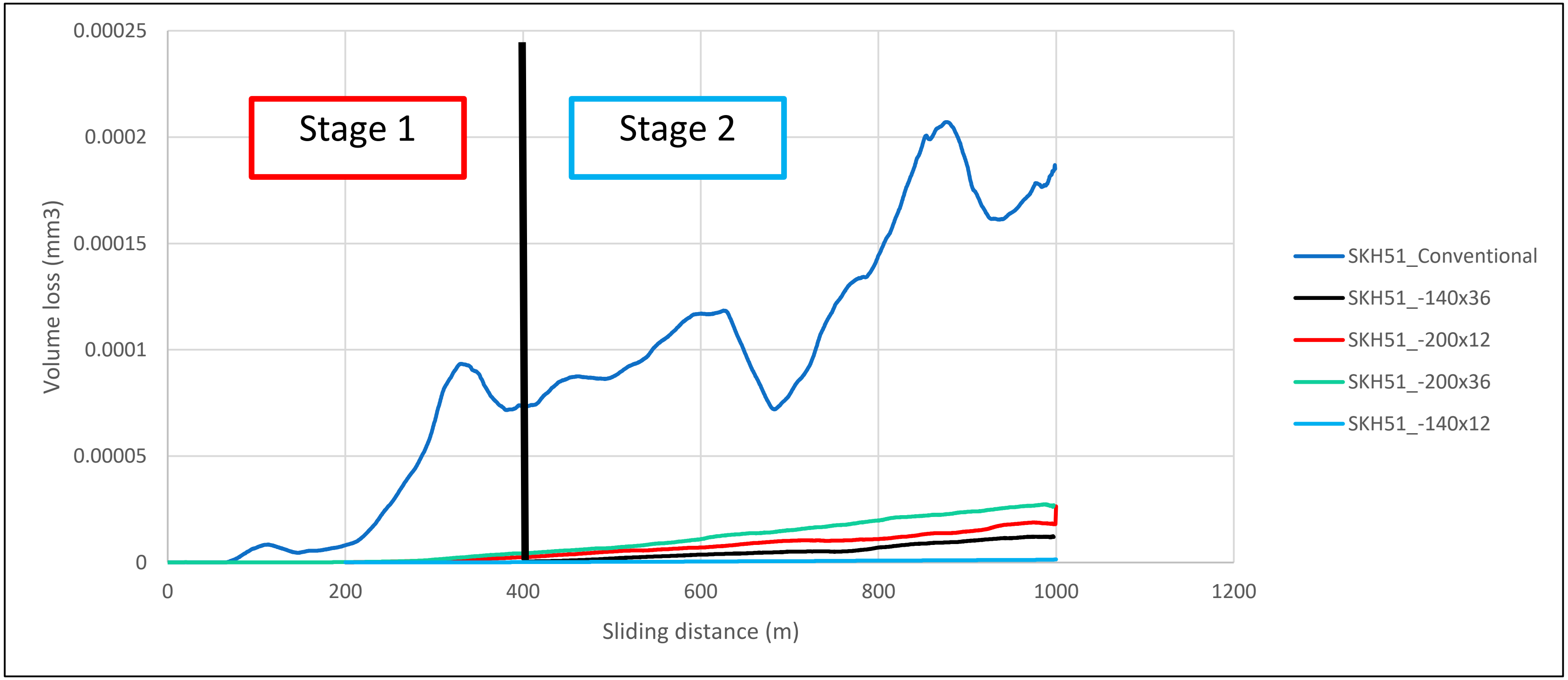
Volume loss of YXR3 under different DCT conditions

Wear Behavior



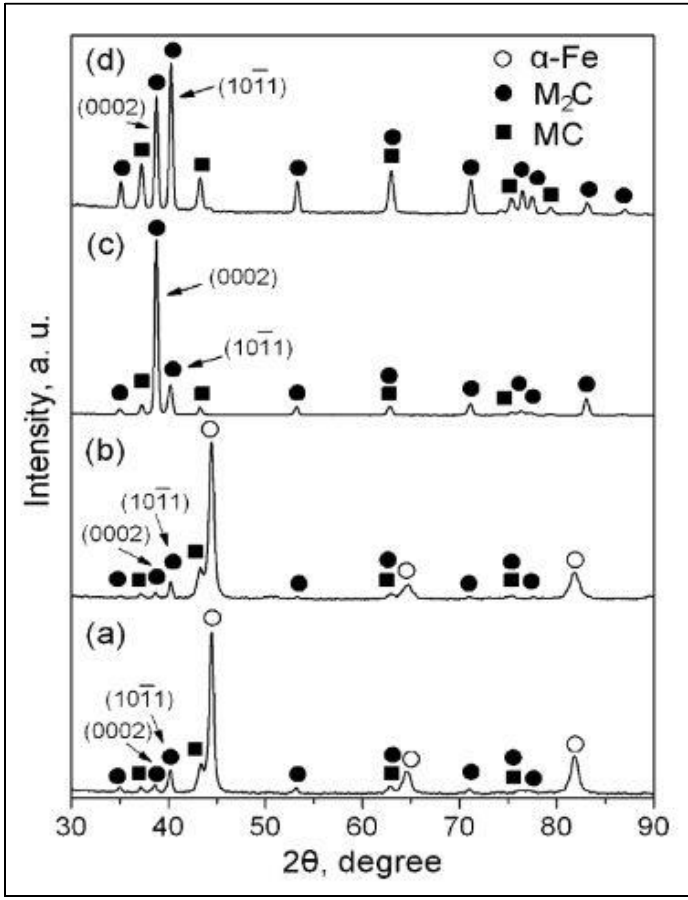
Wear testing Results

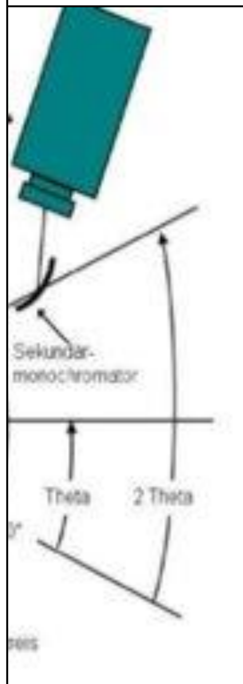
	SKH51				
	Conventional treatment	-140 °C		-200 °C	
		12 hr	36 hr	12 hr	36 hr
Wear Rete (mm3/m) ($x10^{-8}$)	11.7	3.67	3.00	4.00	4.00
Improvement Percentage (%)	-	69 %	74 %	66 %	66 %

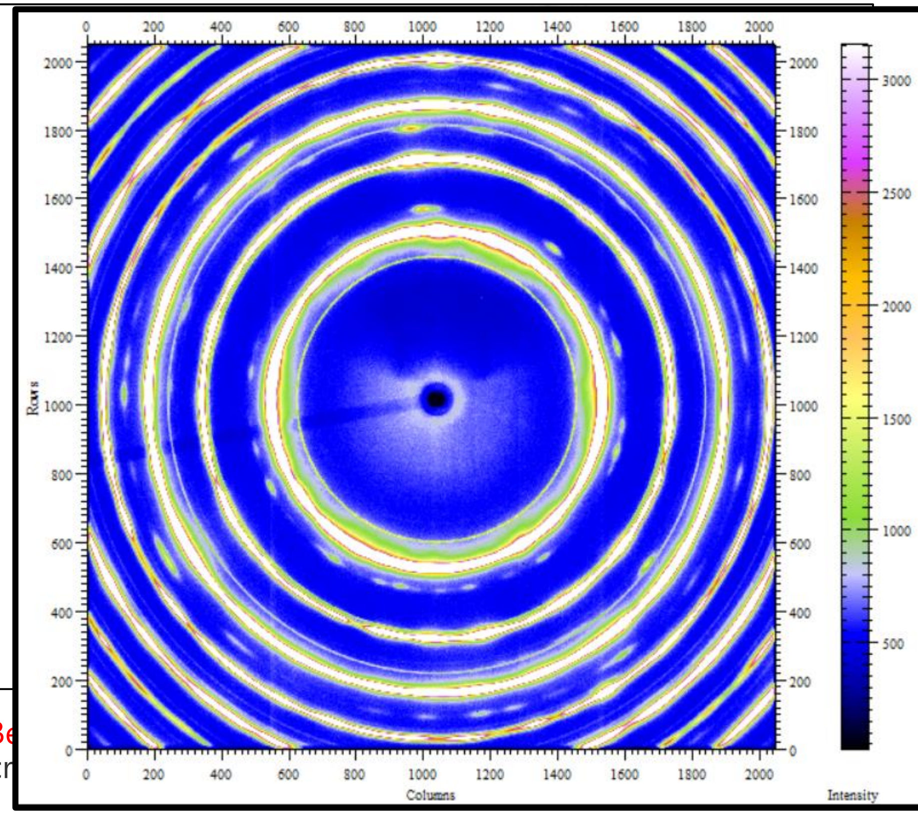


Volume loss of SKH51 under different DCT conditions

What is X-ray Diffraction ?





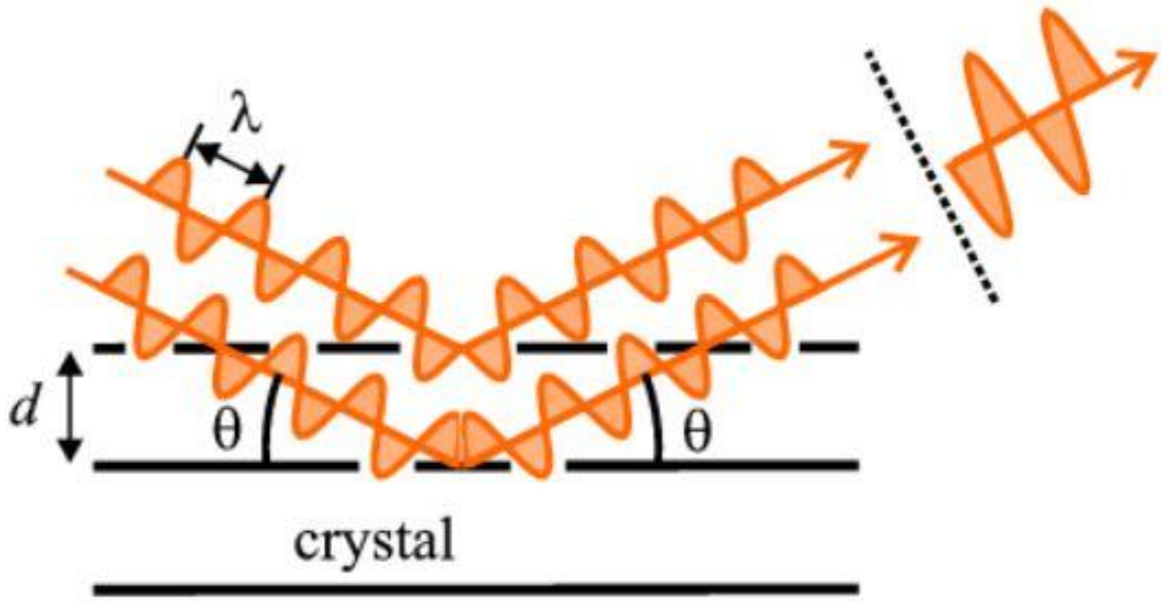


etup; (a) Bragg-Be
definite cr

XRD is a technique used for determining the atomic and molecular structure of a crystal.

Keun Chul Hwang, Sunghak Lee, Hui Choon Lee., " Effects of alloying elements on microstructure and fracture properties of cast high speed steel rolls Part I: Microstructural analysis"., Materials Science and Engineering A254 (1998) 282–295

Basic concept of XRD



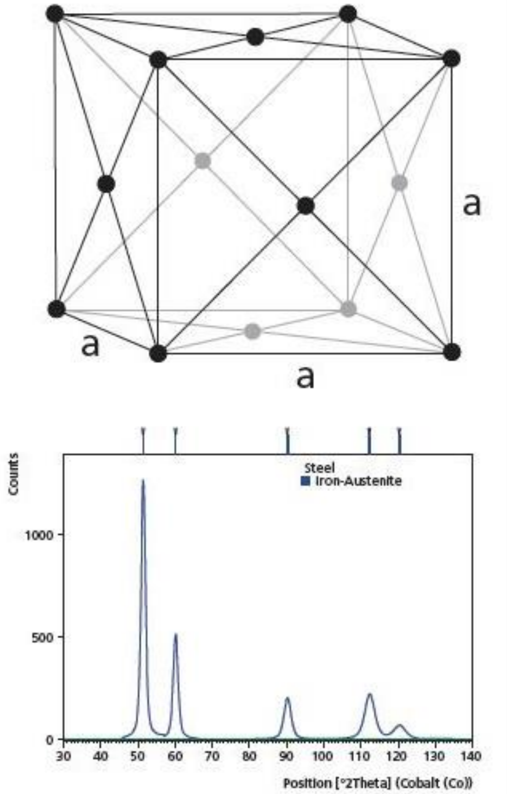
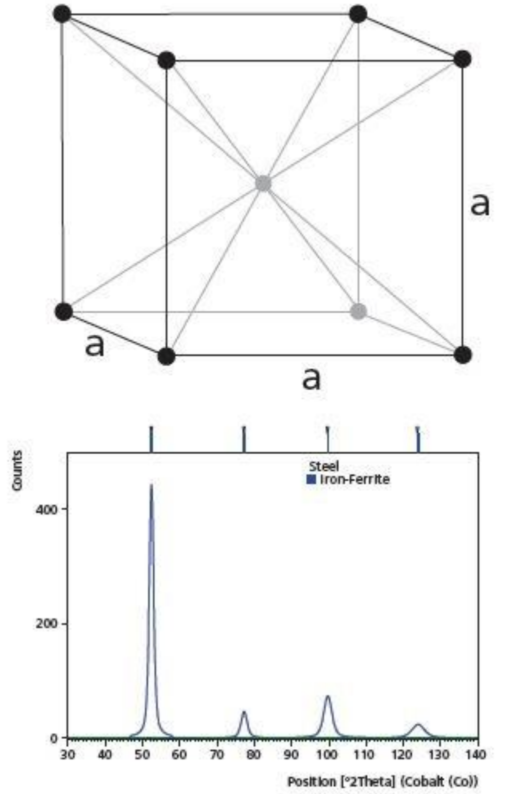
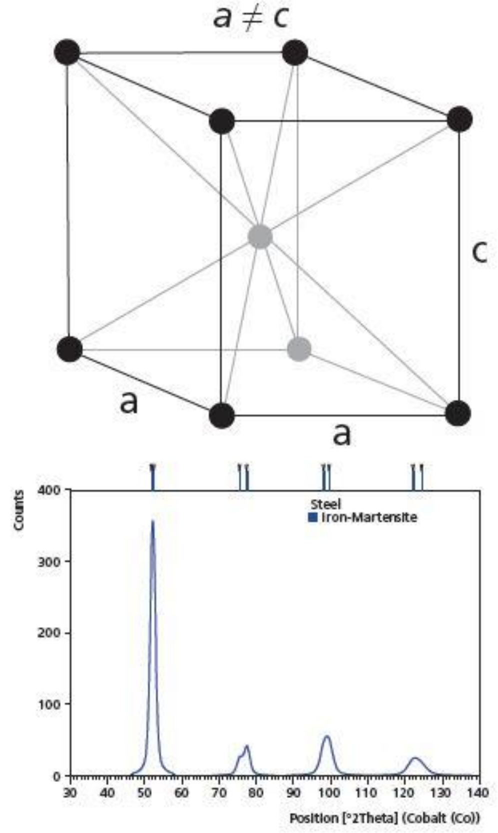
$$n \lambda = 2 d \sin \theta$$

Where:

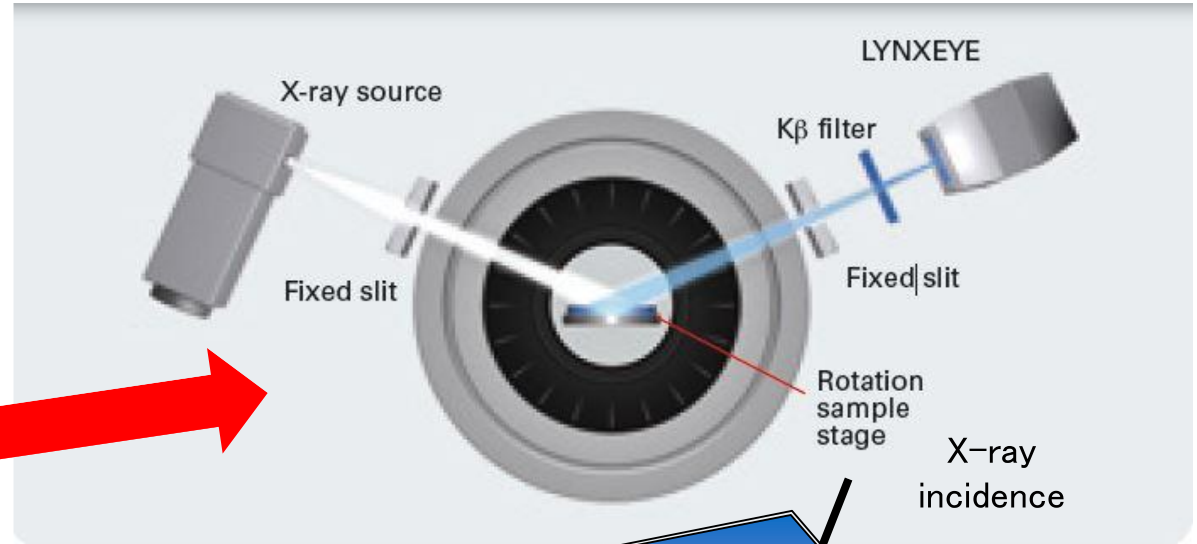
λ is the wavelength of the radiation used,
d is the inter-planar spacing involved.
θ is the angle between the incident (or diffracted) ray and the relevant crystal planes.
n is an integer, referred to as the order of diffraction.

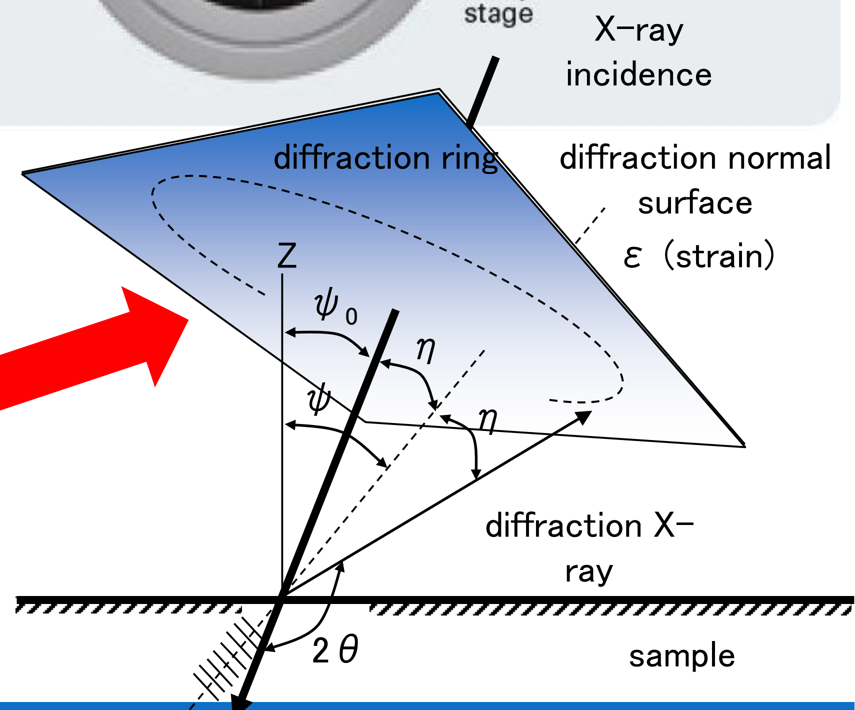
Hall SR, Allen FH, Brown ID (1991). "The Crystallographic Information File (CIF): a new standard archive file for crystallography". Acta Crystallographica. A47 (6): 655–685. doi:10.1107/S010876739101067X

Basic concept of XRD

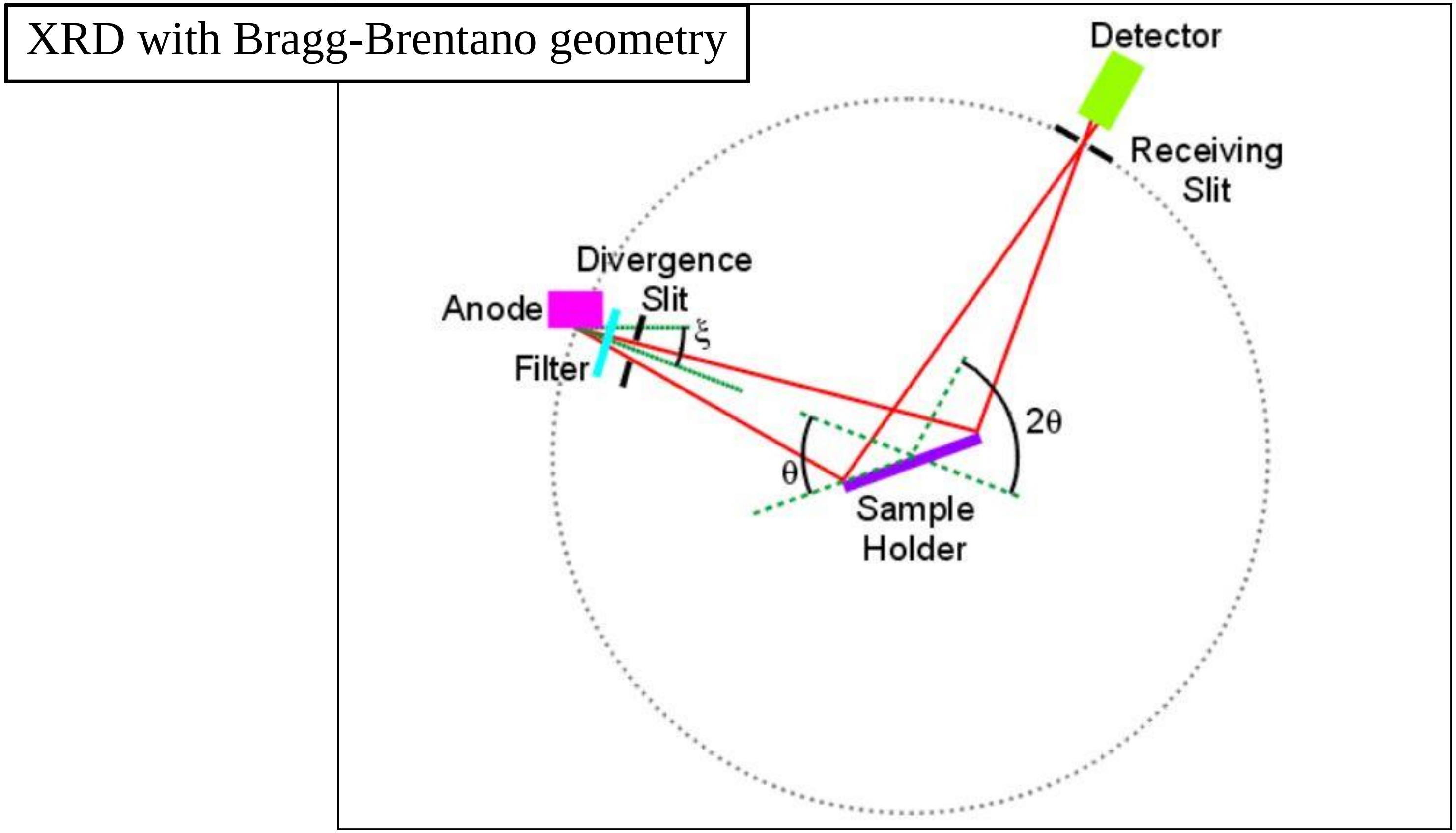
Austenite	Ferrite	Martensite
FCC	BCC	BCT
a = 0.3575 nm*	a = 0.2868 nm*	a = 0.2861 nm* c = 0.2923 nm*
		

Geometry of an X-Ray Diffractometer



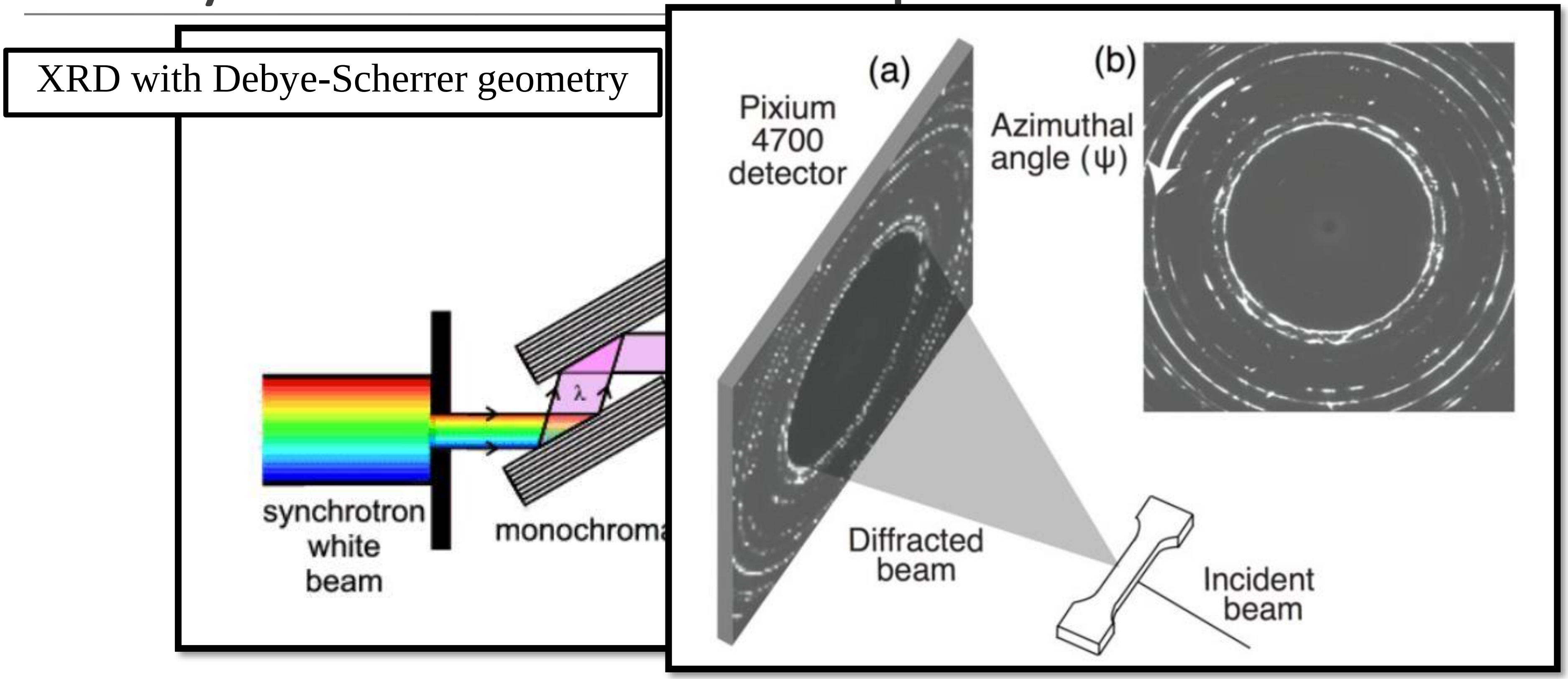


Bragg-Bentano Setup



The earliest flat-plate diffractometers had poor intensities and peak widths due to lack of focussing. By contrast the modern flat-plate diffractometer has both good peak intensities and excellent resolution due to focussing of the diffracted beam. This reflection geometry, in which the divergent and diffracted beams are focussed at a fixed radius from the sample position, is commonly referred to as Bragg-Brentano geometry.

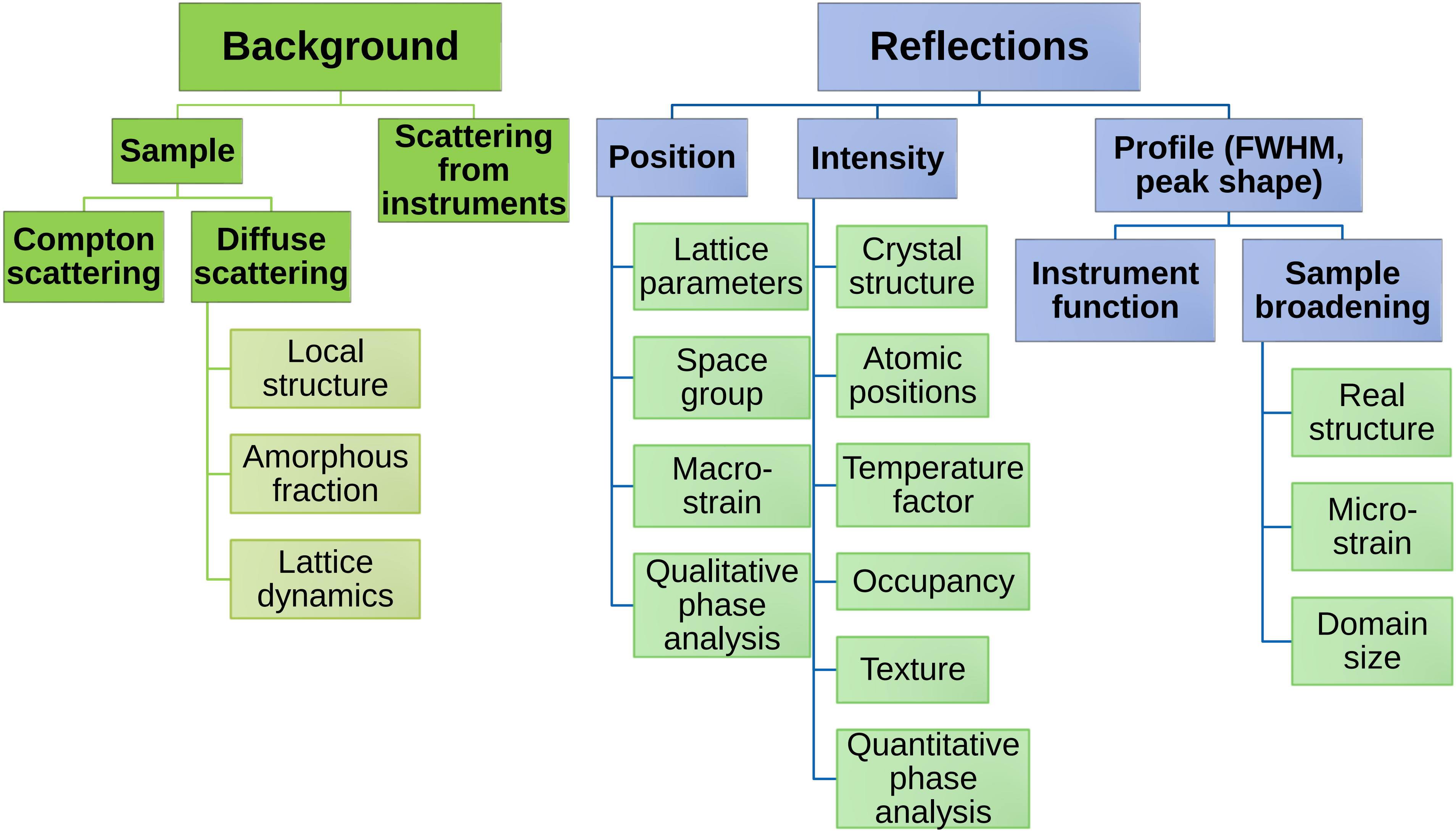
Debye-Scherrer Setup



The term *Debye-Scherrer* is named after the originators, Debye, Scherrer and Hull, and is one of the oldest known powder diffraction geometries, though originally it was used only with photographic film on a "powder diffraction camera". It uses a near-parallel incident beam of X-rays with sufficient cross-section to bathe the whole powder-sample. One of its virtues is its simplicity as illustrated by the following schematic of the Debye-Scherrer camera/diffractometer.

a) Schematic of the synchrotron X-ray diffraction setup, (b) Complete Debye-Scherrer rings from tetragonal martensite

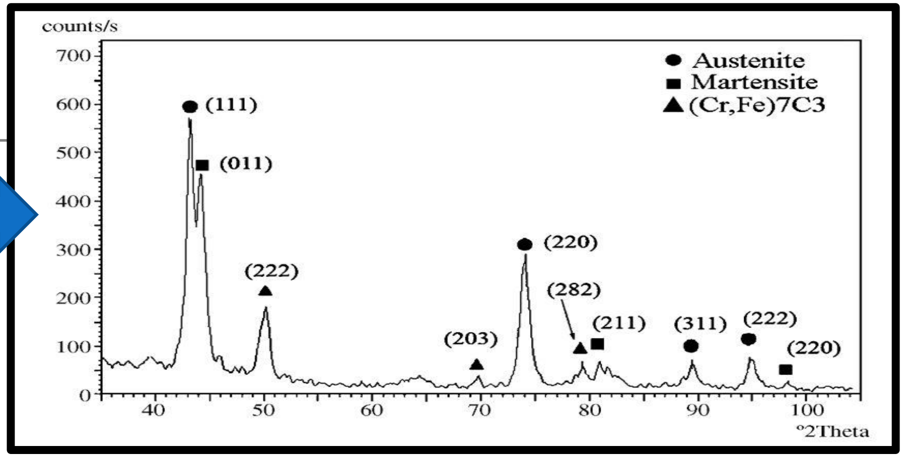
General information content of PXRD data



Ref. R.E. Dinnebier & S.J.L. Billinge, Powder diffraction theory and practice 2008.

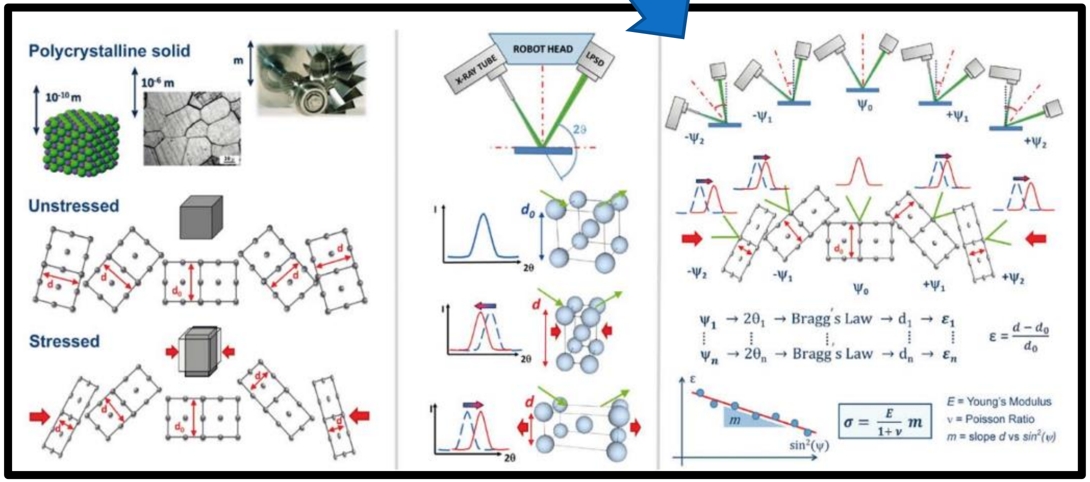
Applications

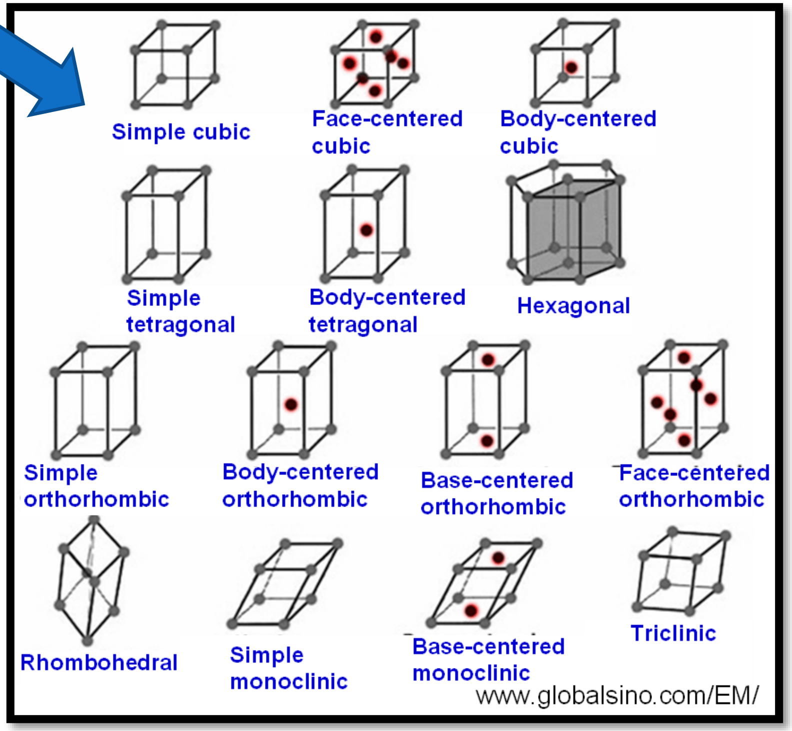
- Phase Identification



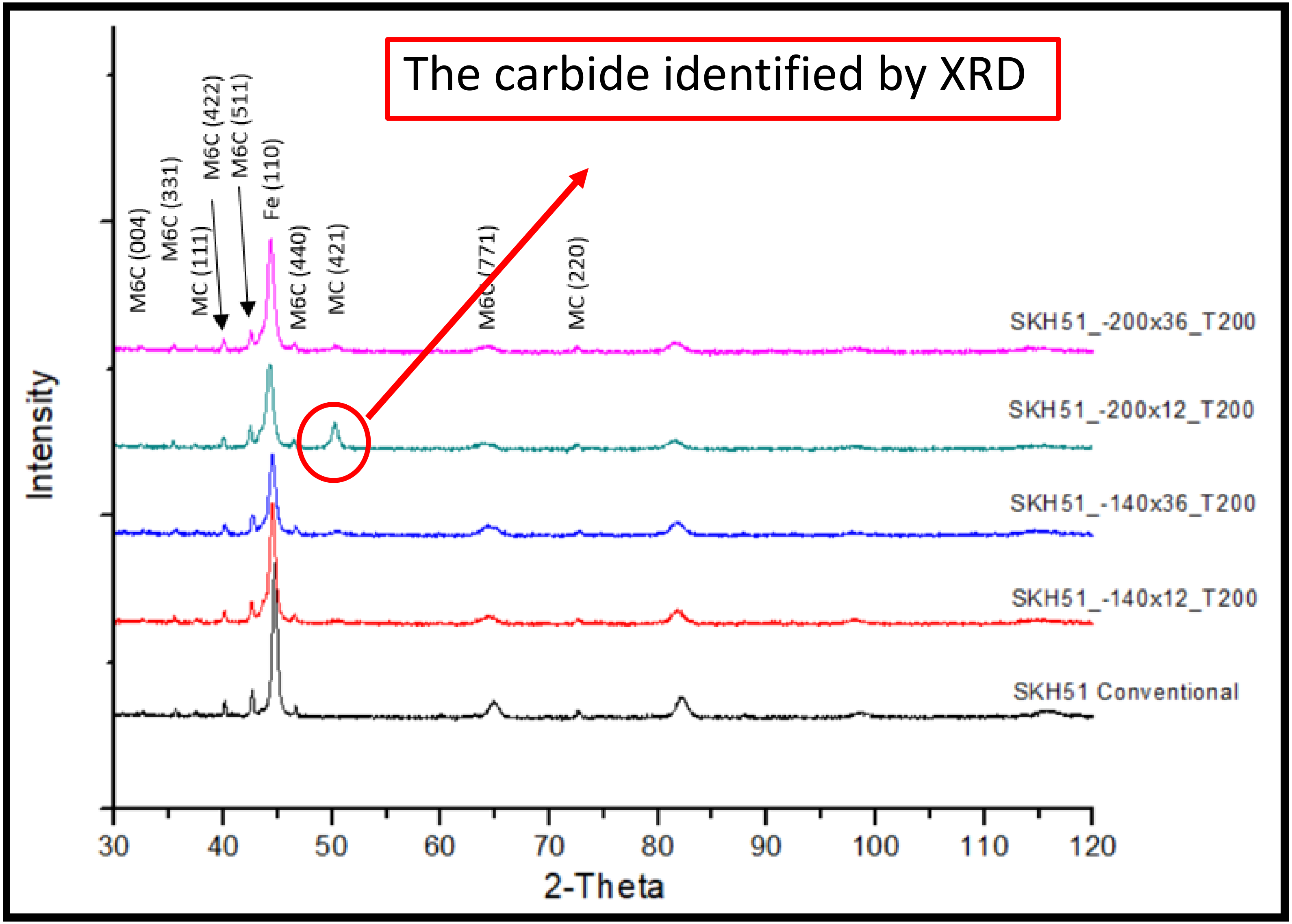
- Unit cell lattice parameters and Bravais lattice symmetry.

- Residual Stress and Strain





DCT Effect by XRD SKH51



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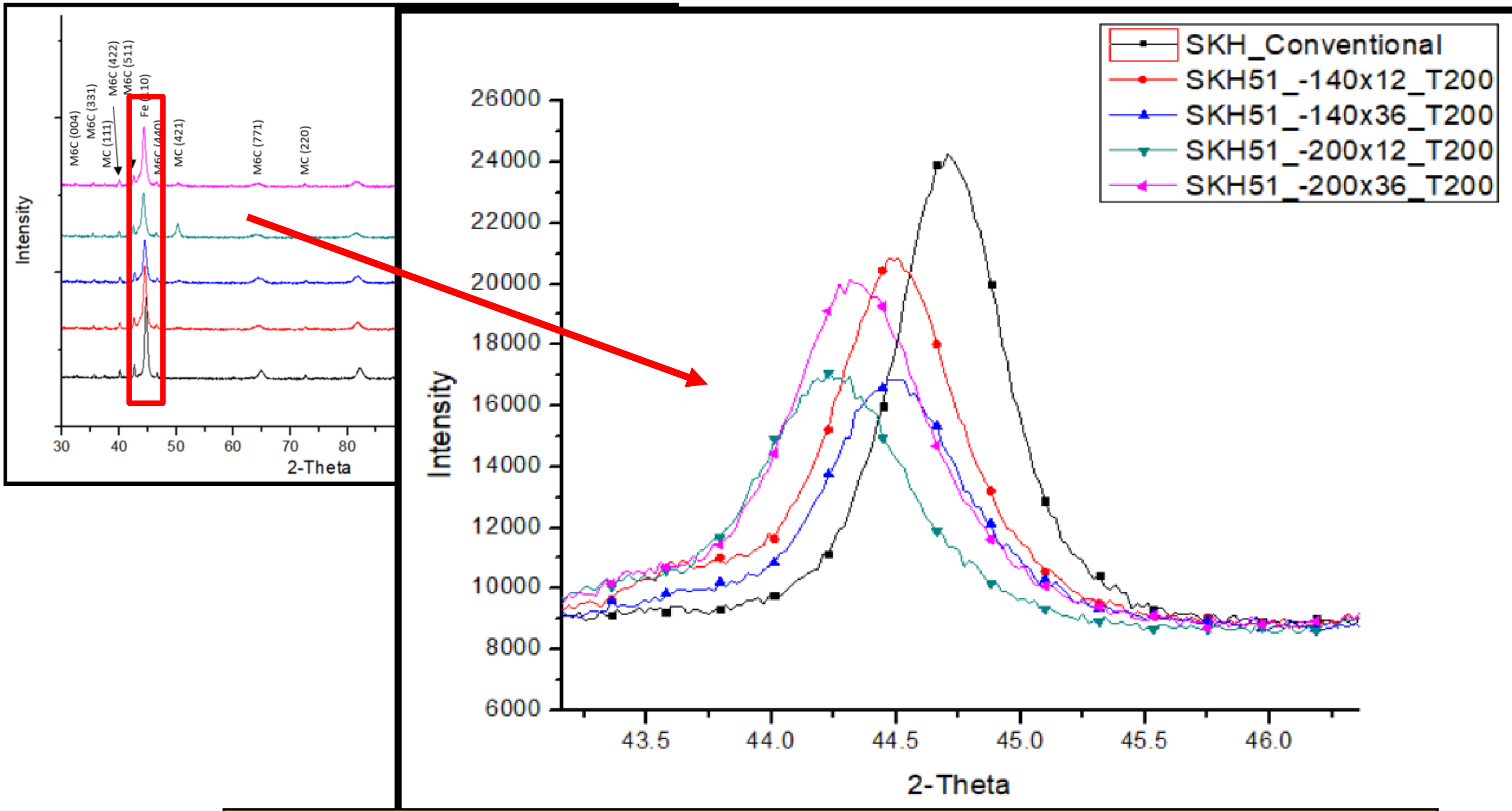

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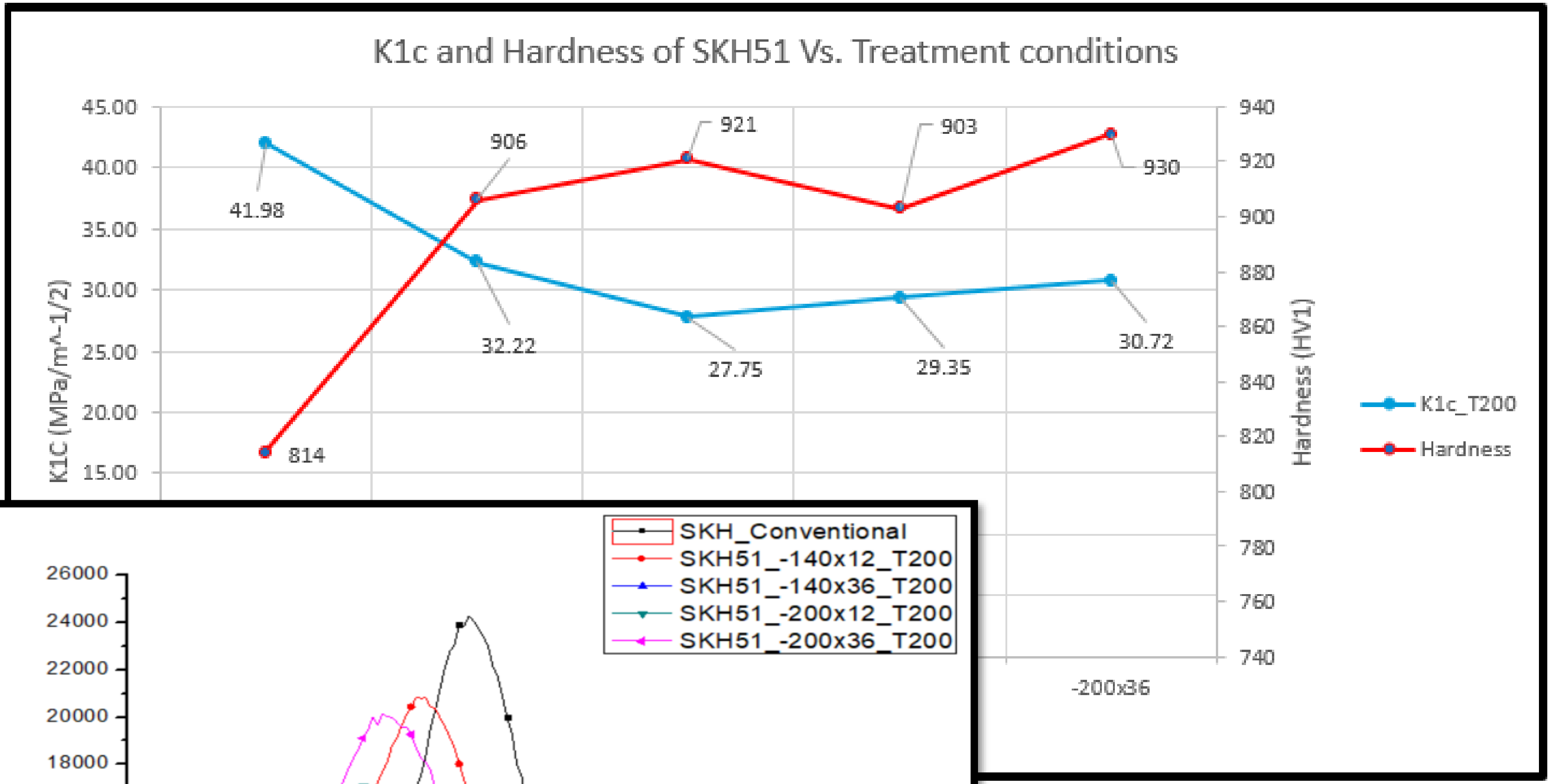
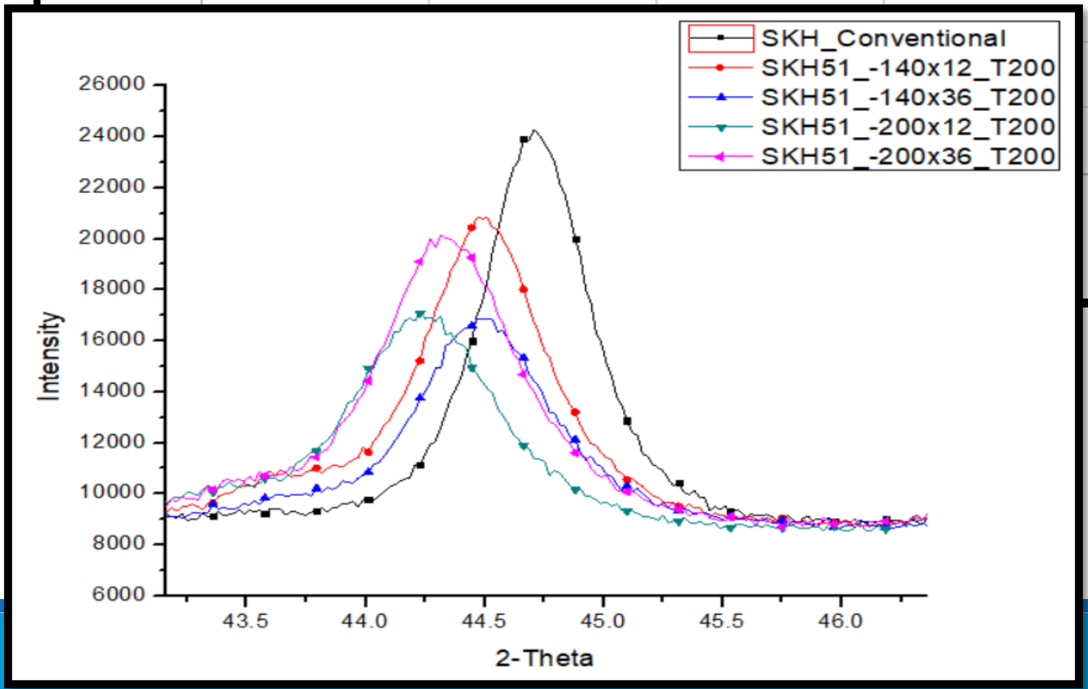
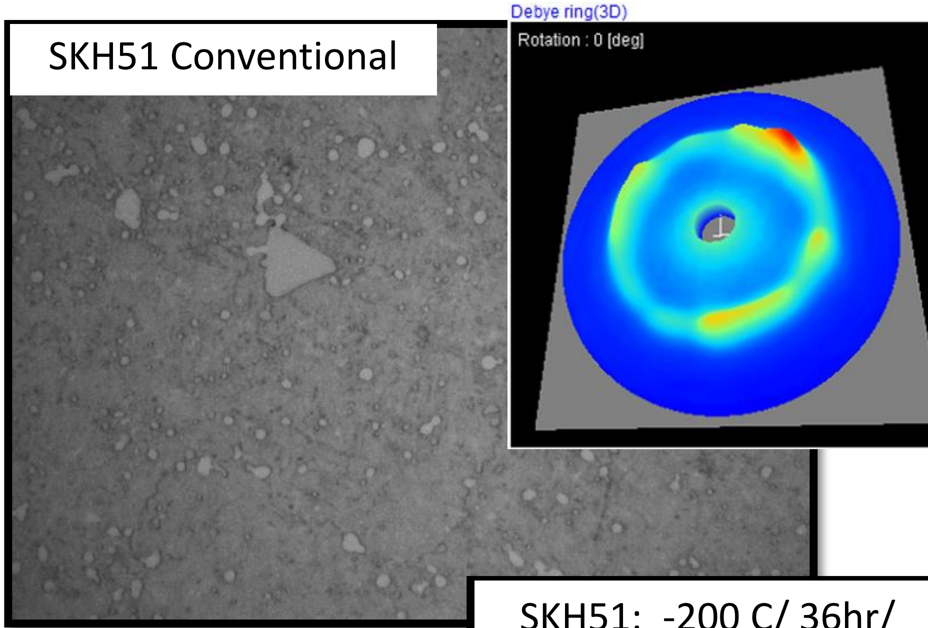
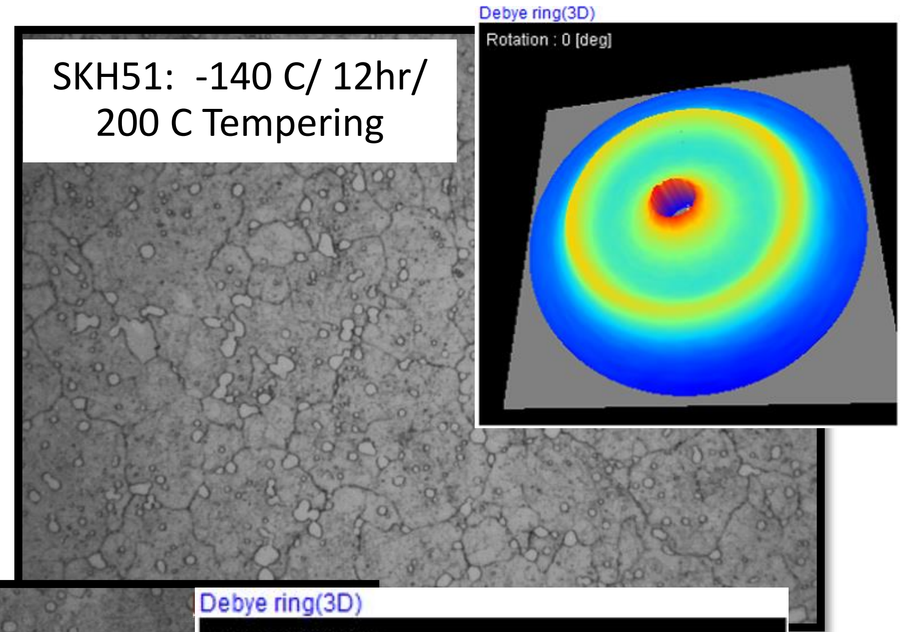
DCT Parameters Effect on SKH51



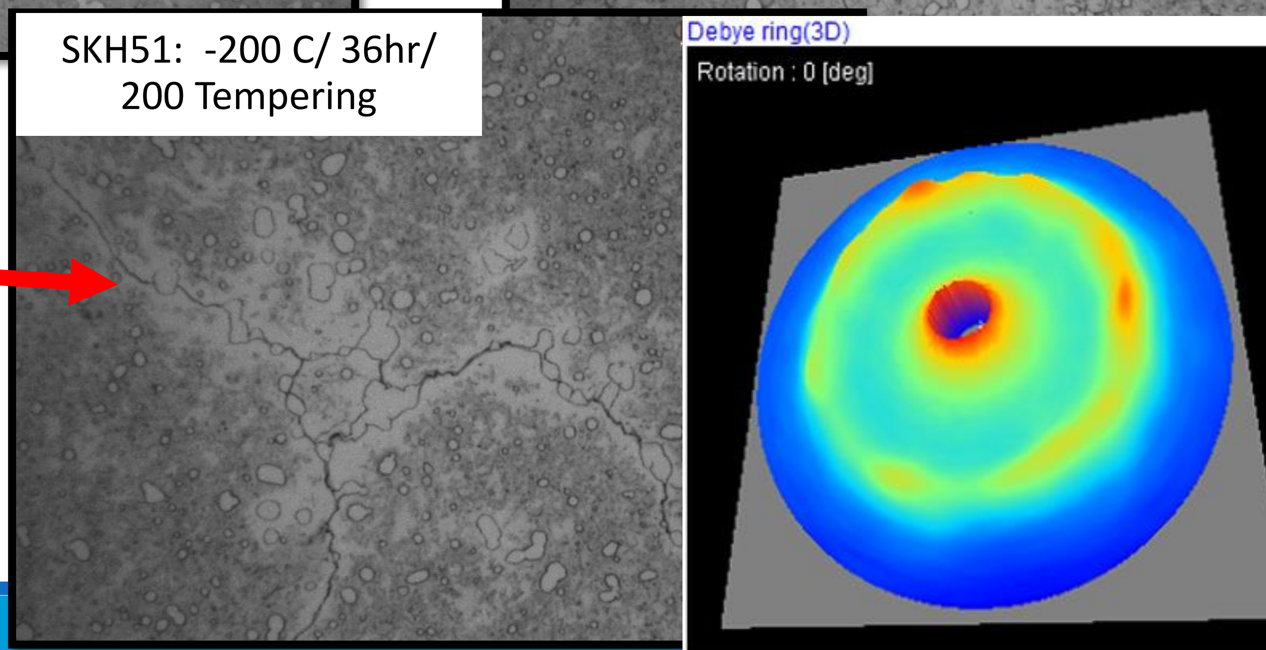


DCT Effect by XRD SKH51

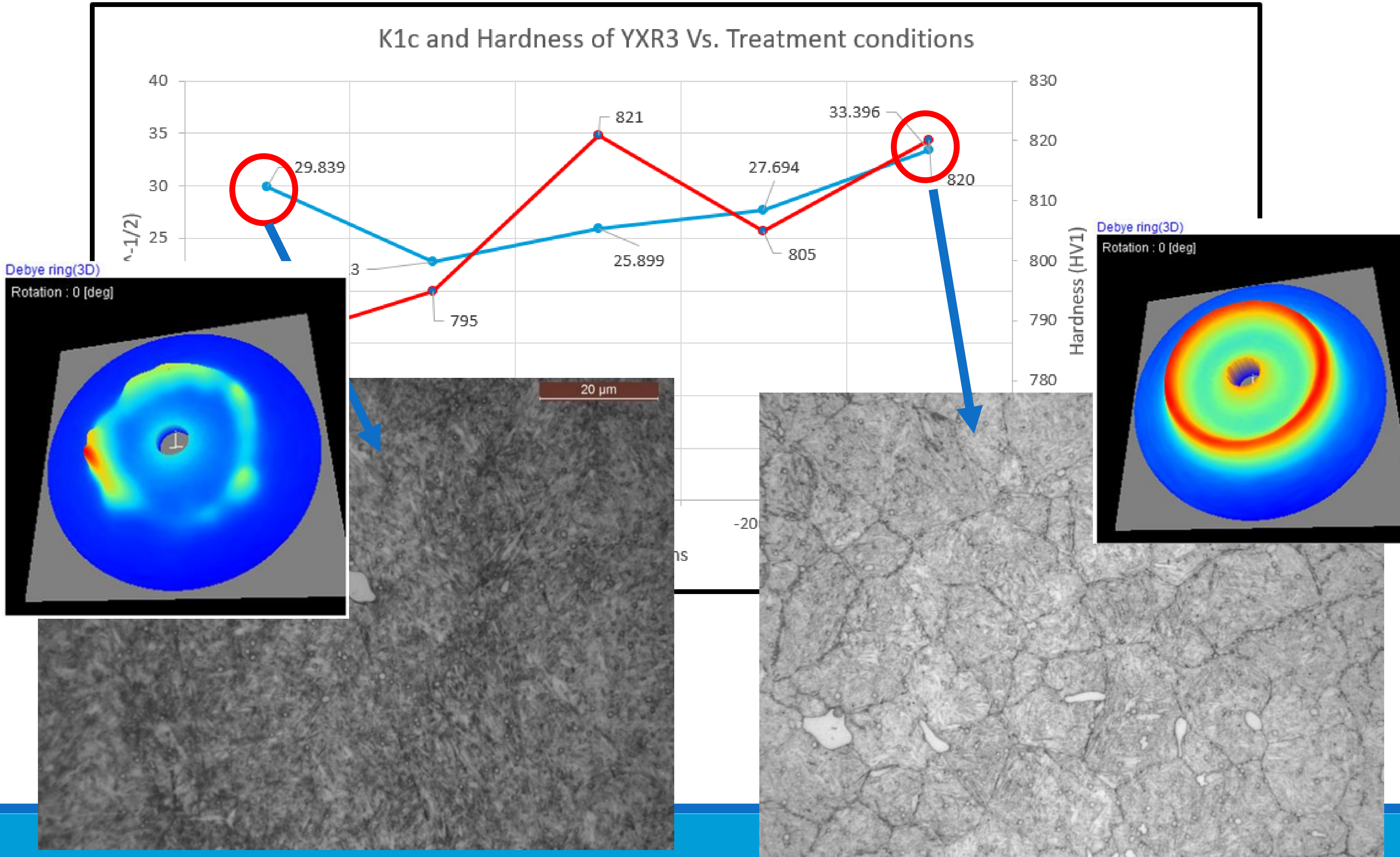




Crack !!!



DCT Parameters Effect on YXR3



Conclusions

1) DCT process improves the wear resistance of high-speed steel up to 80% compared to the conventional heat-treatment process.
2) DCT refining both carbide precipitation and martensite matrix in the microstructure resulting in wear mechanism improvement in both in Stage 1 and Stage 2.
3) The effect of DCT on tool materials need to be investigated separately
4) Scratch testing technique is a useful technique capturing the significant change in microscopic level (micro toughness) which cannot be investigated by conventional bulk testing technique i.e. Charpy impact test.
5) XRD is a useful technique to study the microstructure change, phase identification and residual stress analysis.

THANK YOU

FOR

YOUR ATTENTION