Relationships between Tensile and Fracture Mechanics Properties and Fatigue Properties of Large Plastic Mold Steel

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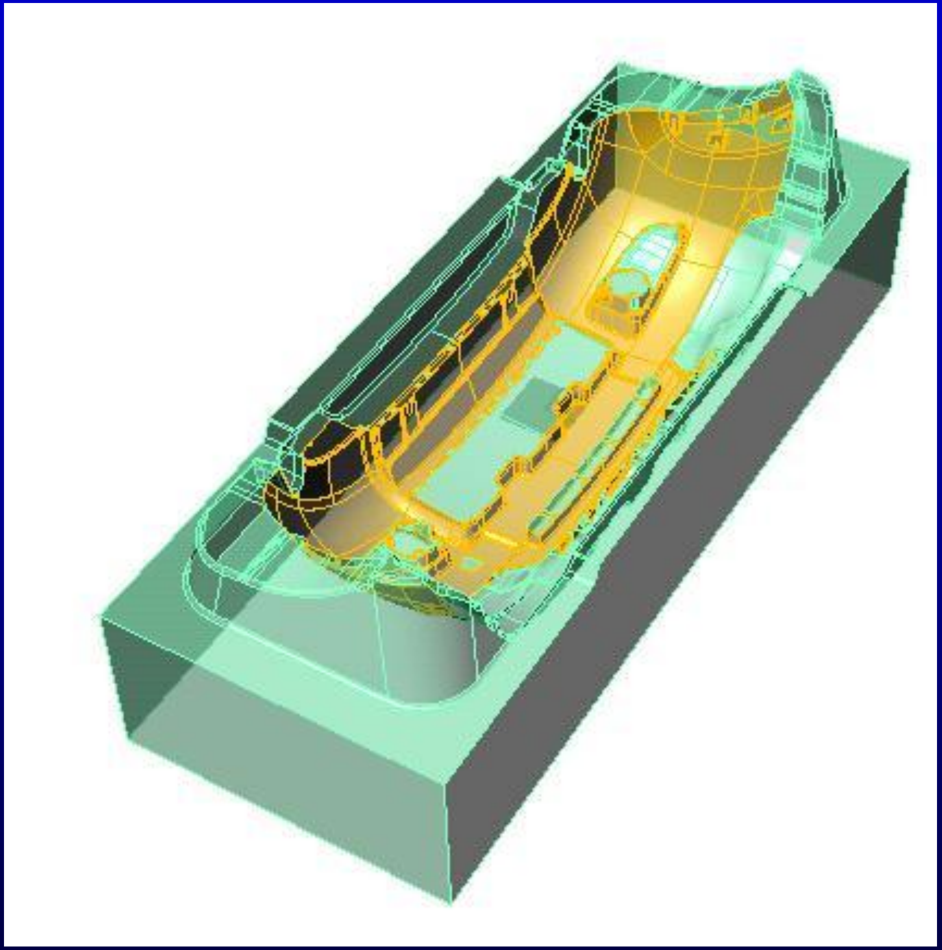
Overall views of a bumper mould.



Summary

- Production cycle and critical issues of large plastic moulds
- Sampling pattern and re-heat-treatments
- As-received microstructures
- Mechanical properties and fatigue behaviour of as-received and re-heat-treated steel
- Fracture surfaces
- Conclusions

Plastic molds machined from 1x1x2 m forged and pre-hardened steel blooms

Applications

- ***automotive components (bumpers, dashboards, …)***

Stresses

- ***applied stresses:***
  - injection pressure
  - thermal gradients
  - notch effects
  - wear by reinforced resins flow
  - fatigue (millions of pieces)
- ***stresses raised by:***
  - cracks (improper weld bed depositions),
  - abnormal operations (incomplete extraction).

- *Experience-based design, no usual defect-allowance calculation procedure*
- *Reported macroscopically brittle in-service failures*

- *different microstructures expected at increasing depths after quench*
- *any microstructure could be found at mold face*

Usual Production cycle (I)

➢ *Steel composition*

	C	Cr	Mn	Ni	Mo	Si	S	P
1.2738 40CrMnNiMo8-6-4	0.35 - 0.45	1.8 - 2.1	1.3 - 1.6	0.9 - 1.2	0.15 - 0.25	0.2 - 0.4	<0.03	<0.03
Examined bloom	0.42	2.0	1.5	1.1	0.21	0,37	0.002	0.006

➢ *Steel mill operations*

ingot casting (ESR refining is not possible)
forging to 1x1 m sections
dehydrogenization
oil quenching
tempering (one or more stages)

Usual Production cycle (II)

- ***Commercial warehouse operations***

  removal of rough and decarburized surfaces (up to 10-20 mm)

  sawing to requested dimensions

- ***Mold machining shop operations***

  chip-removal and/or electrical-discharge machining to the mold shape grinding with or without polishing in selected areas

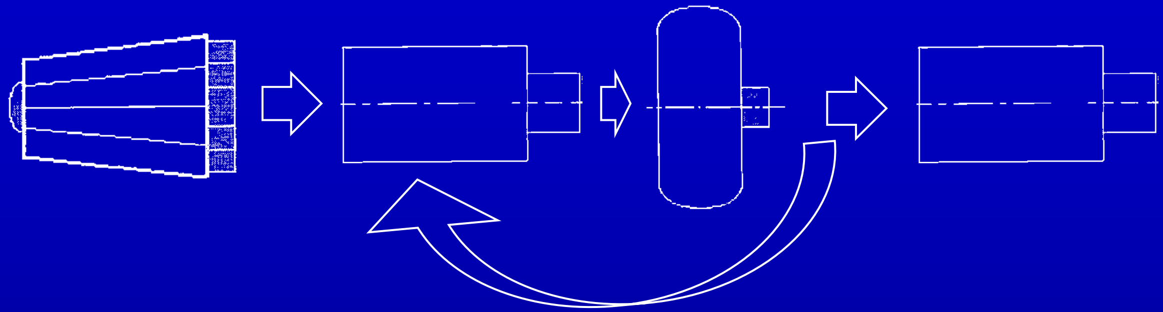
  local surface treatments

  eventual corrections using weld bed depositions

Usual Production cycle (cont.)

Forging

- comparable ingot and bloom section
- some repeated forging steps

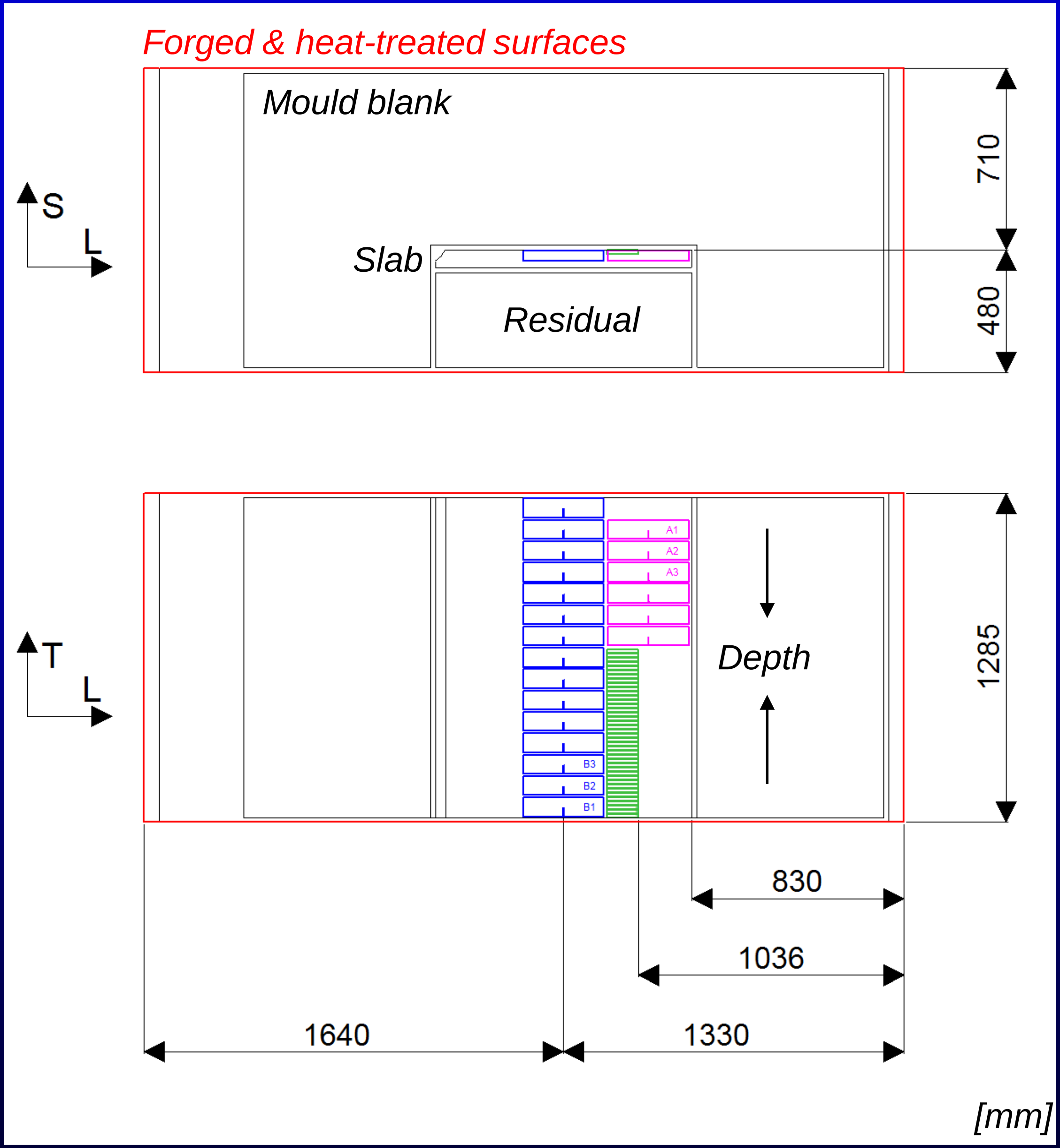


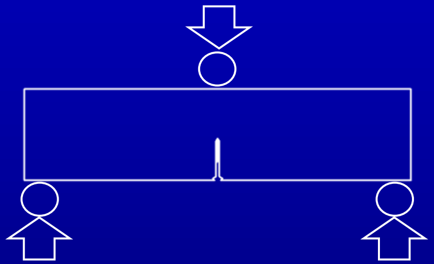
- total reduction ratio much lower than in rolling (and not comparable)

Heat treating in air

Step	Temperature	Duration
hydrogen removal		a few days
austenitizing	840-880°C	1-2 days
oil quench	-	-
tempering to 330-300 HB (one or more stages)	550-600°C	1-2 days (each stage)

Experimental (I): sampling of the original bloom





38 mm thick K_{IC} specimens (LT)

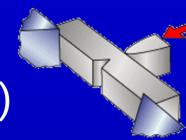
- As-received
- Individually re-heat-treated

Experimental (II): sampling pattern & re-heat-treatments

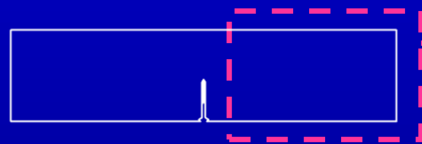
Blanks

- Round tensile specs. (L)

- Metallographic samples
- Re-heat-treated Charpy-V specs. (LT)

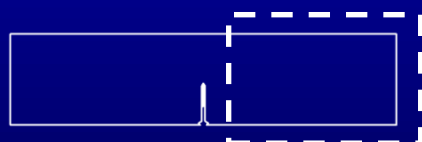


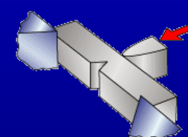
38 mm re-heat-treated K_{IC} specs.



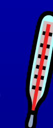
- Round tensile specs. (L)

38 mm as-received K_{IC} specs.





- Charpy-V specs. (LT)

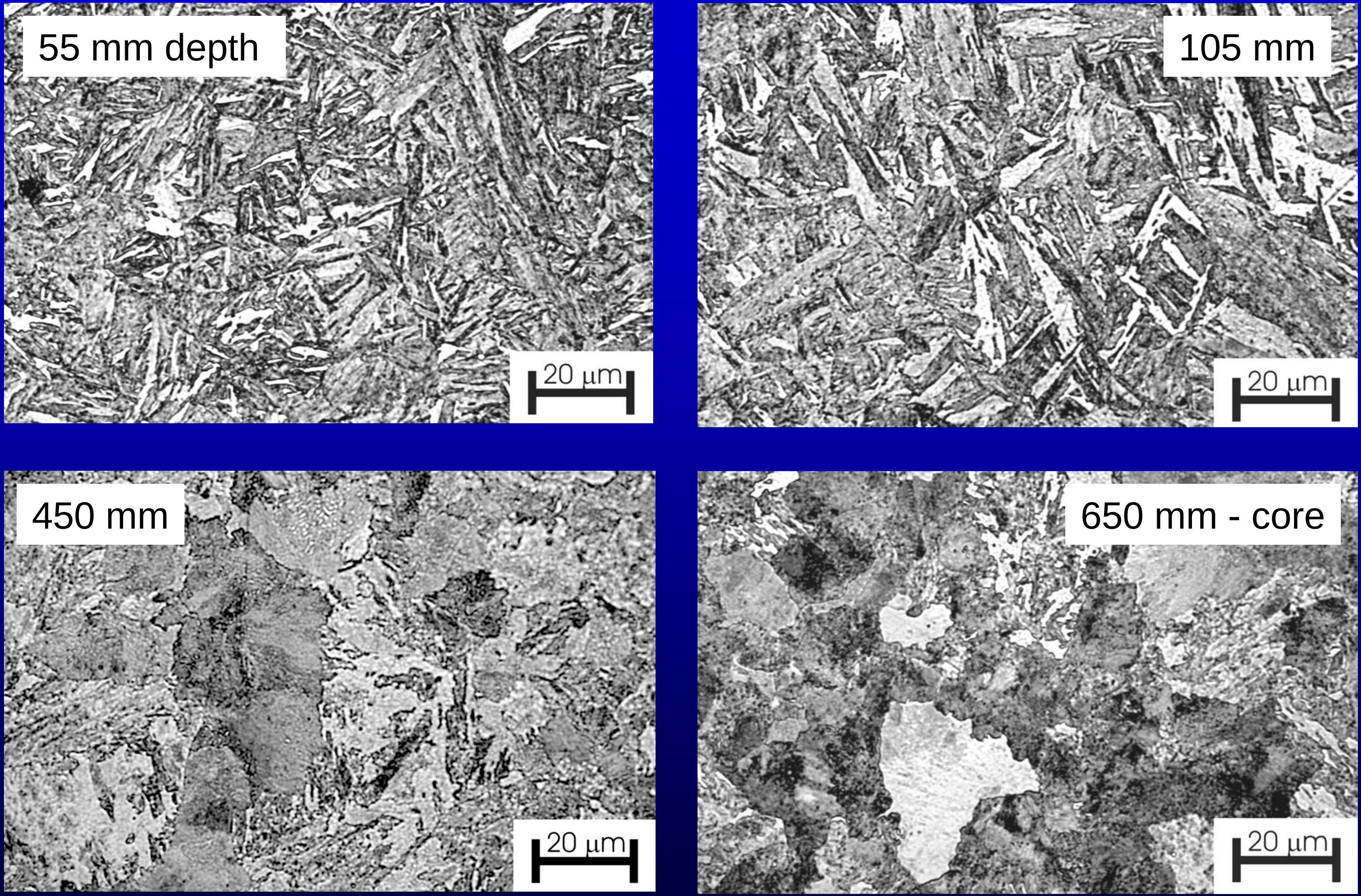


- Rotating bending fatigue specimens (L)

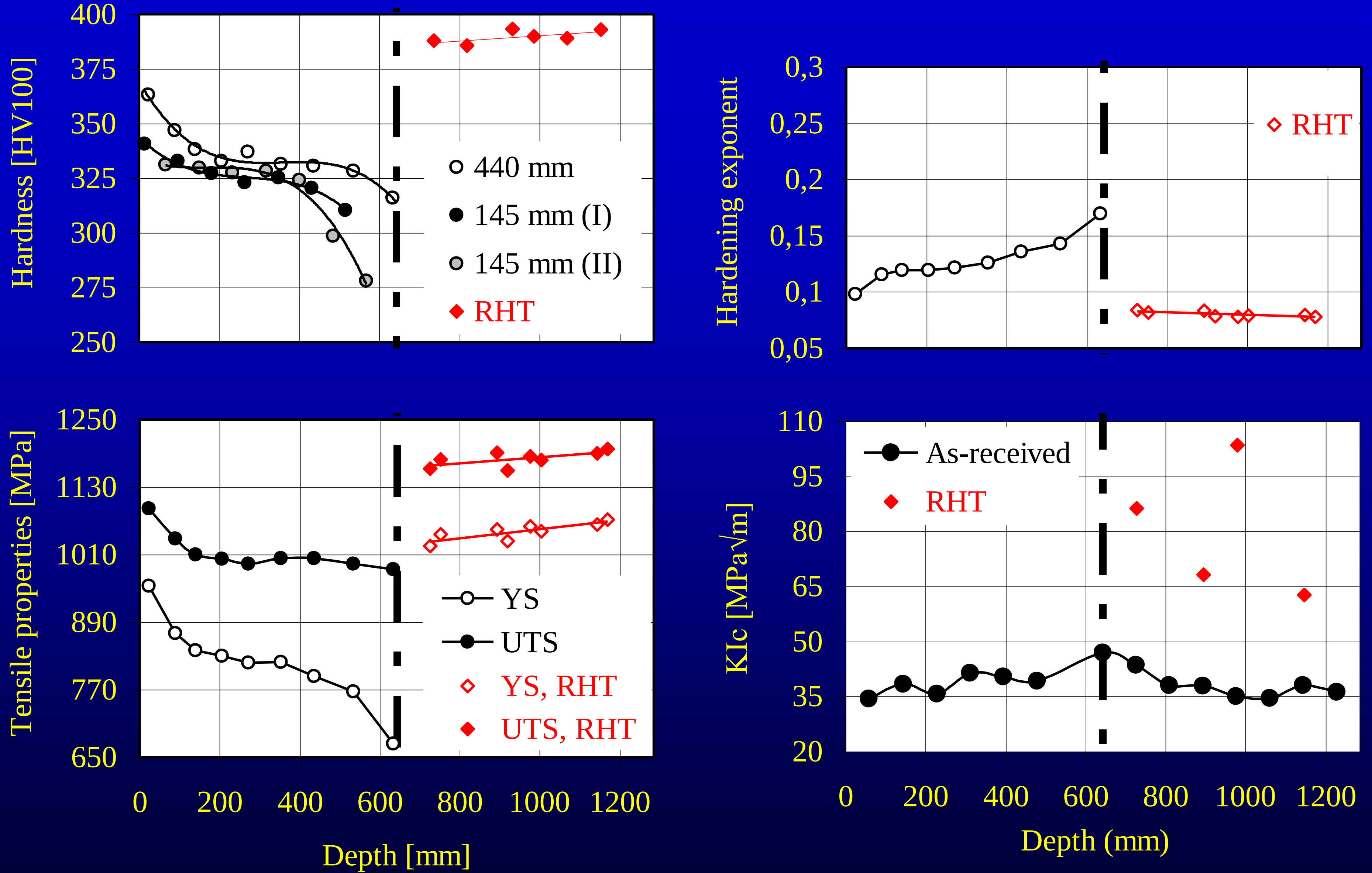
as-received or re-heat-treated

Re-heat-treatments: 860°C ¾h / N_2 or air / 590°C 3h / 550°C 3h

As-received microstructures vs. depth *(Nital etch)*

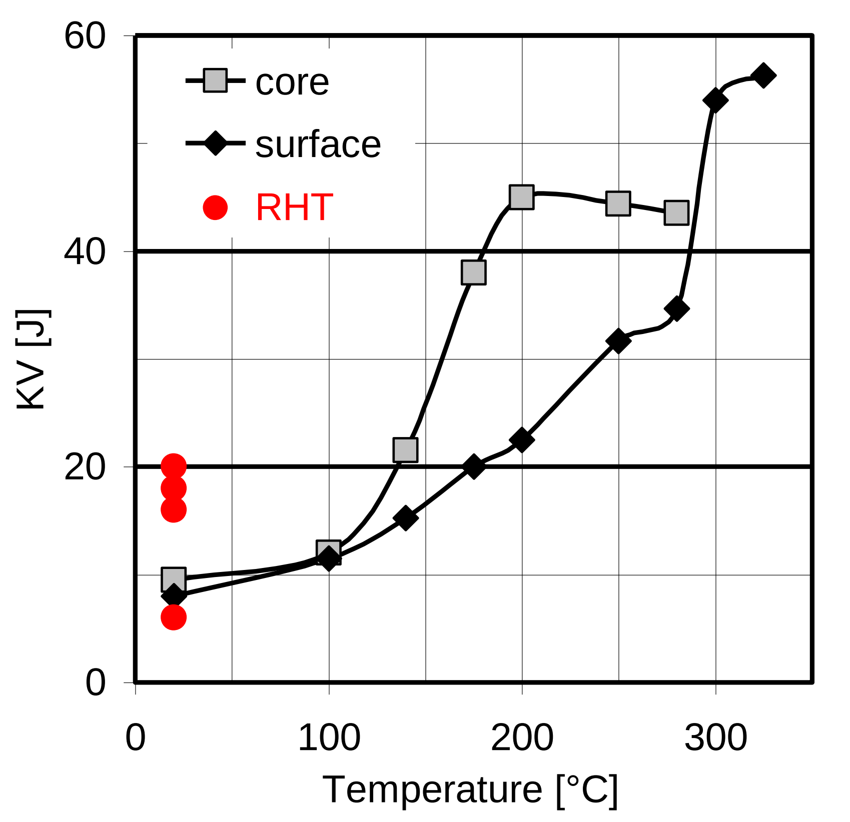


Hardness, tensile and fracture toughness tests

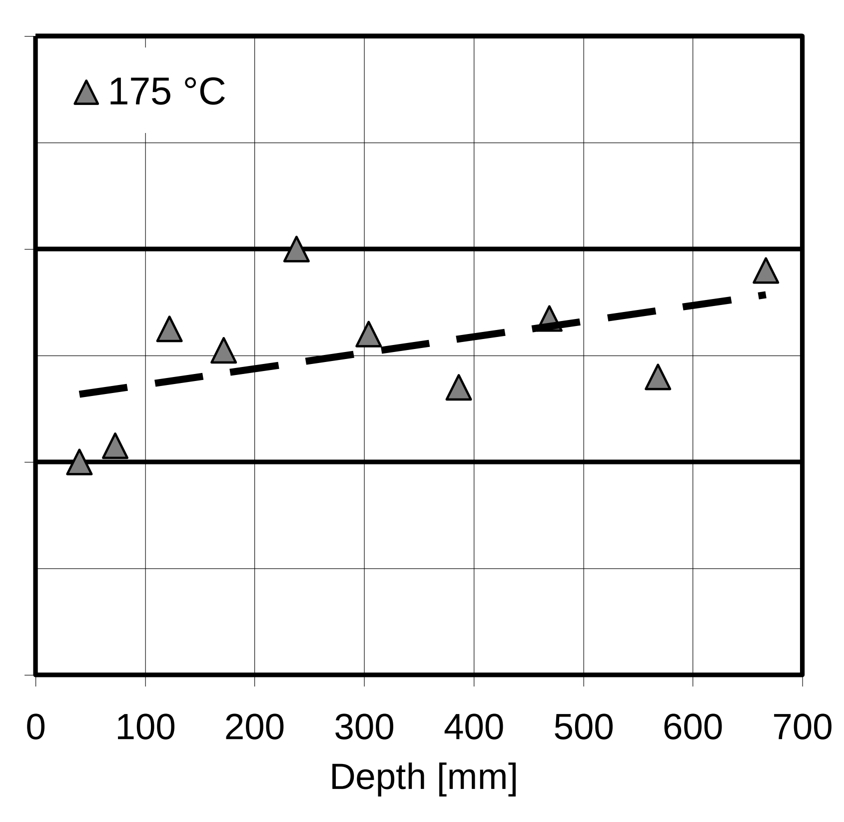


Charpy-V tests & transition curves

Transition curves



175 °C tests



As received steel

Rotating bending fatigue tests – 4.2 Mcycles endurance limit

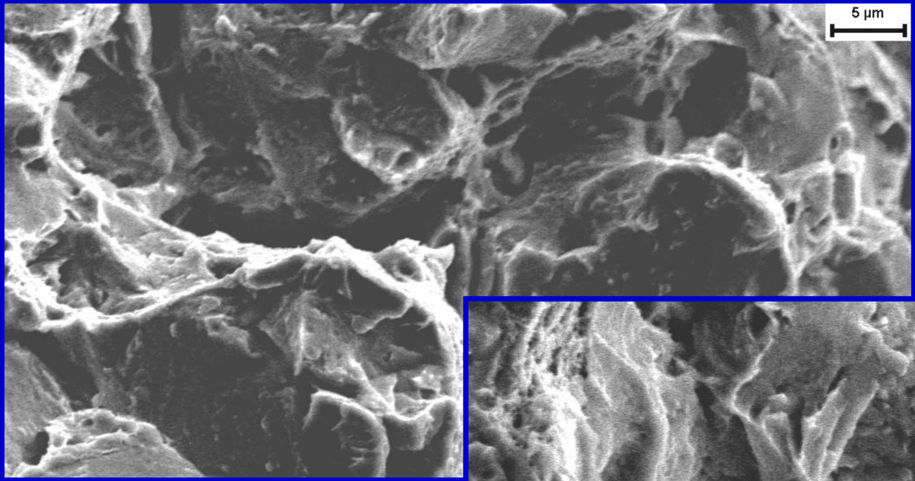
Staircase method (example below: core as-received specimens)

test n.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	X	0
[MPa]																	
500								X				X				2	0
490							O		X		O		X			2	2
480						O				O				X		1	2
470			X		O										O	1	2
460		O		O												0	2
450	O															0	1

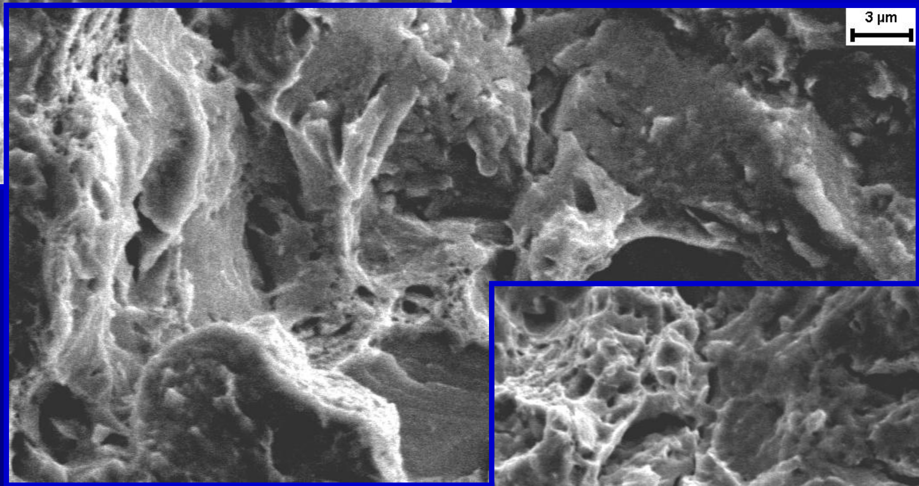
Survival Probability	Stress [MPa]			
	As-received		Re-heat-treated	
	Core (~560 mm)	Surface (~140 mm)	Core (~560 mm)	Surface (~140 mm)
10%	518	581	638	706
90%	469	537	577	694
50%	493 19	559 17	608 24	700 5

25% increase

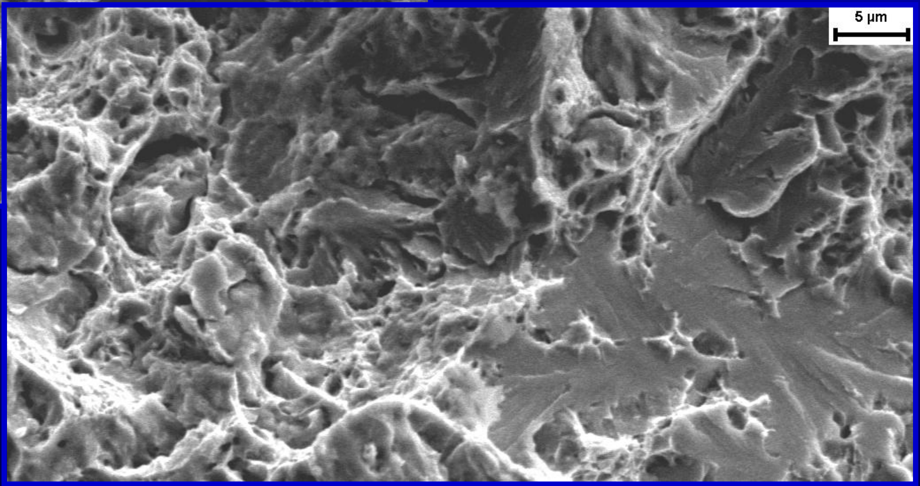
Fractography (I): Charpy-V test - brittle areas (as received specs.)



40 mm depth
intergranular



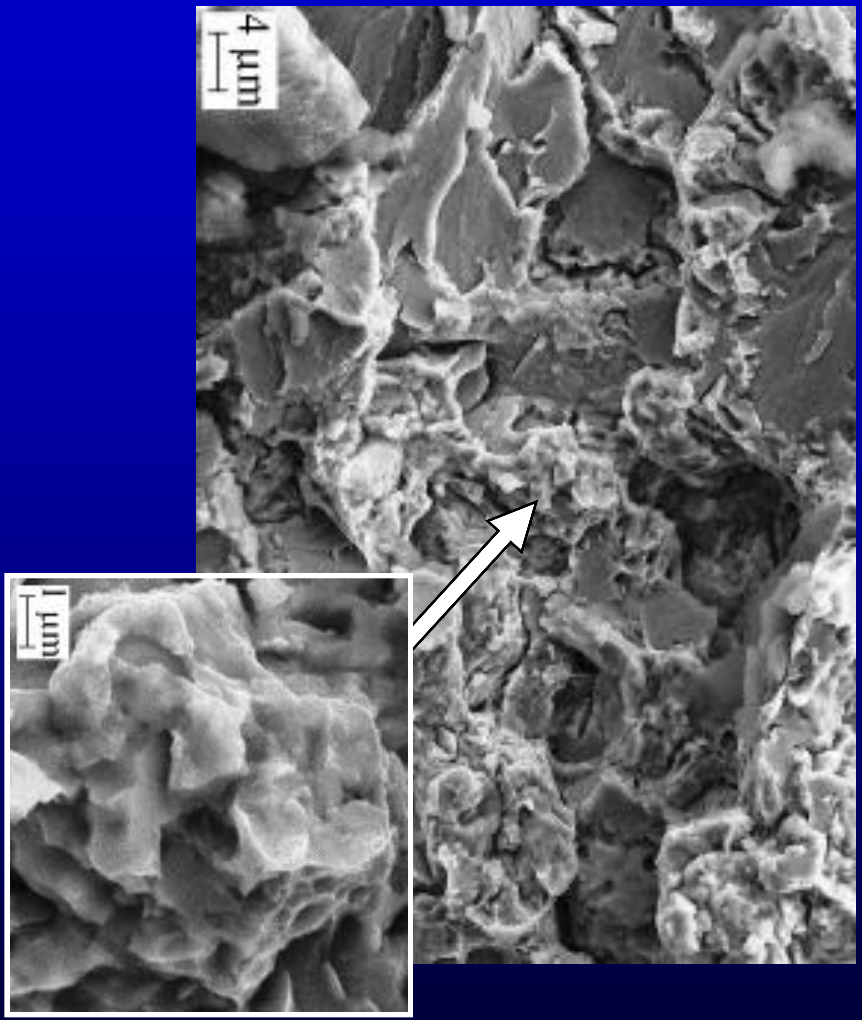
123 mm depth
intergranular & cleavage

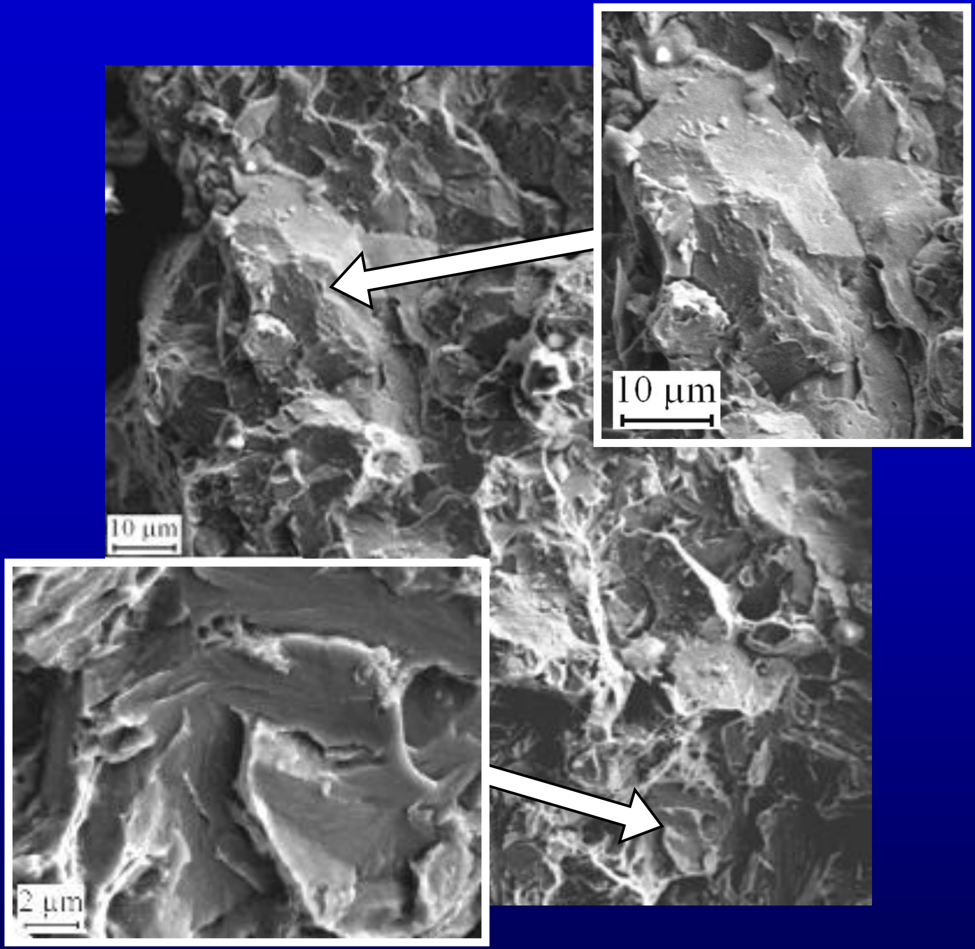


667 mm depth
quasi-cleavage & ductile areas

Fractography (II): K_{Ic} tests – as received specs.

395 mm depth
cleavage & ductile areas

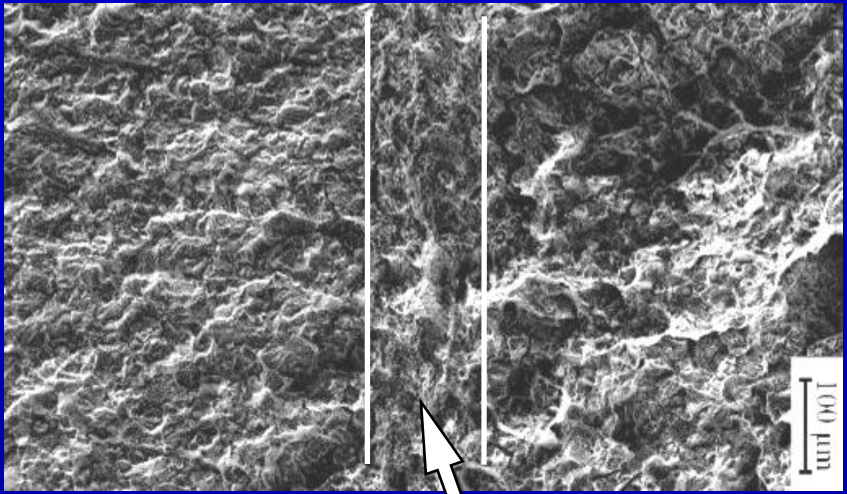


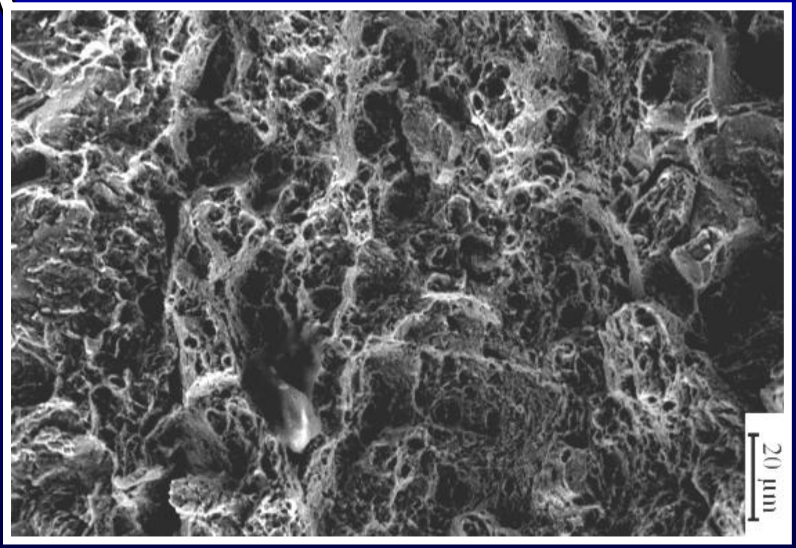


60 mm depth – intergranular & cleavage

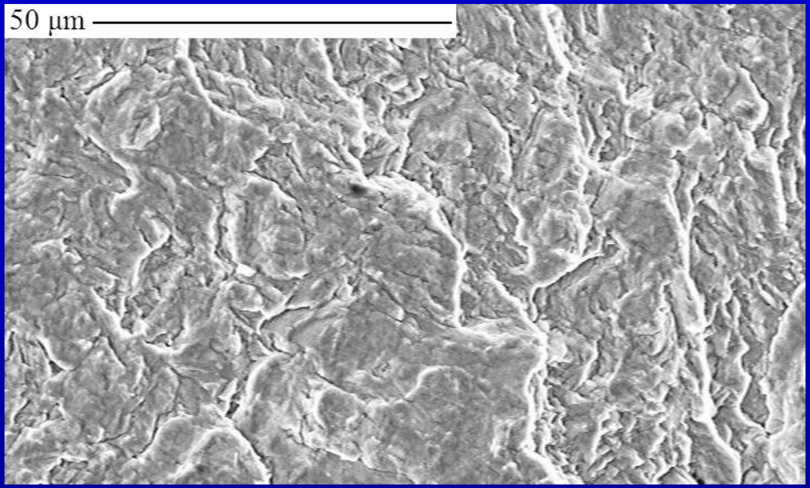
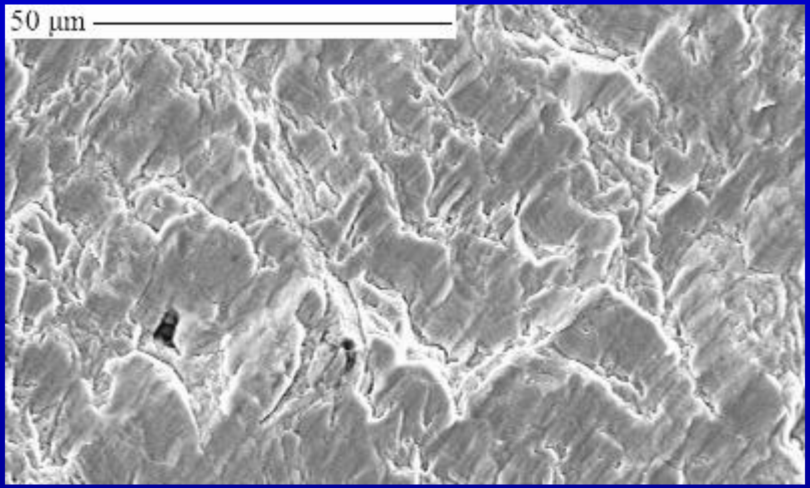
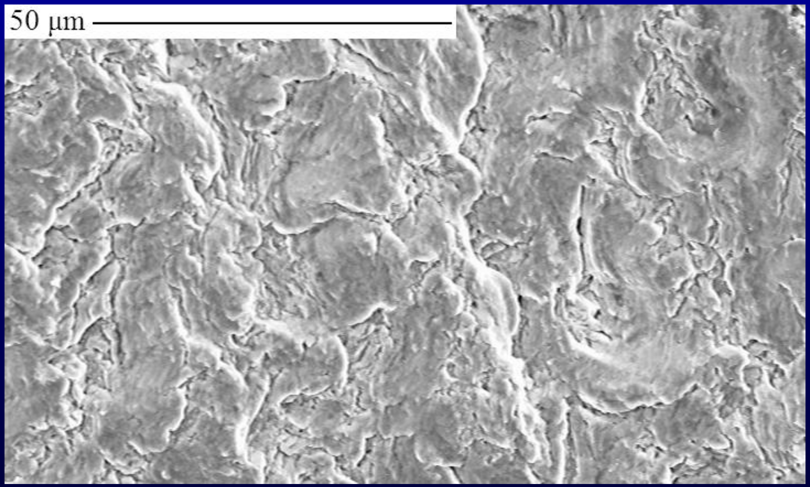
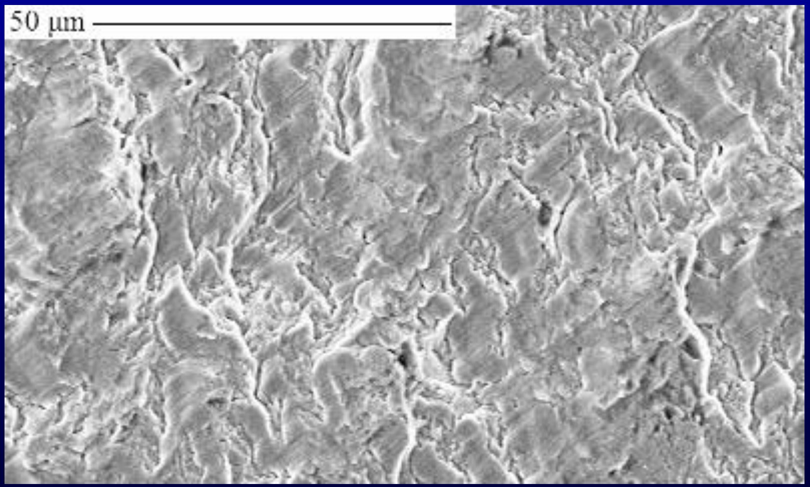
Fractography (III): K_{Ic} tests – re-heat-treated specs.

Fatigue precrack → **Brittle propagation**

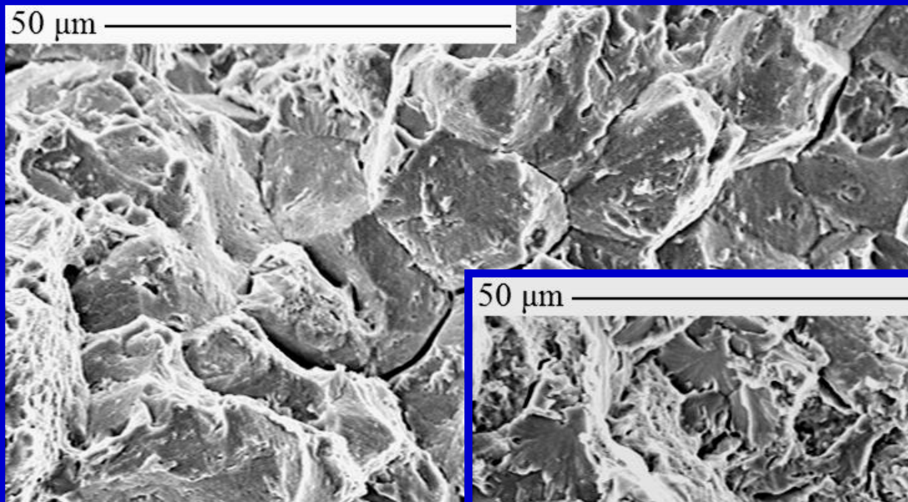




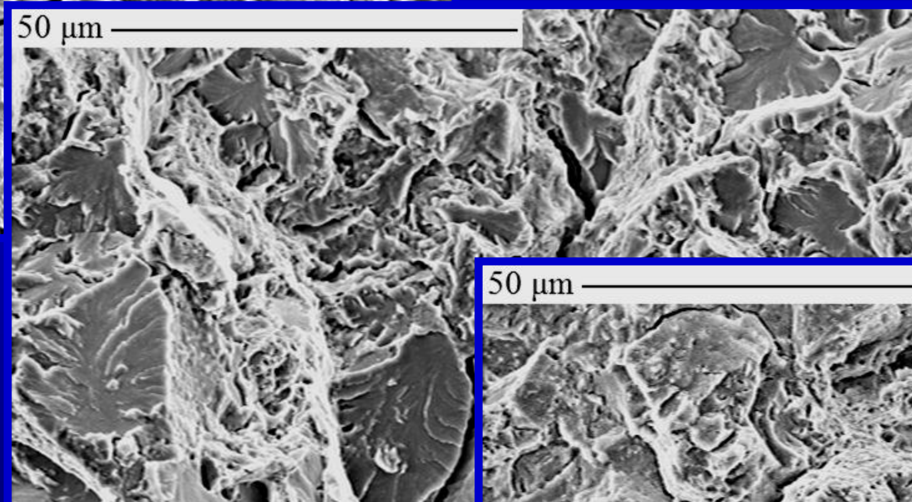
Fractography (IV): fatigue tests – fatigue areas

	As-received	**Re-heat-treated**
Surface (~140 mm)		
Core (~560 mm)		

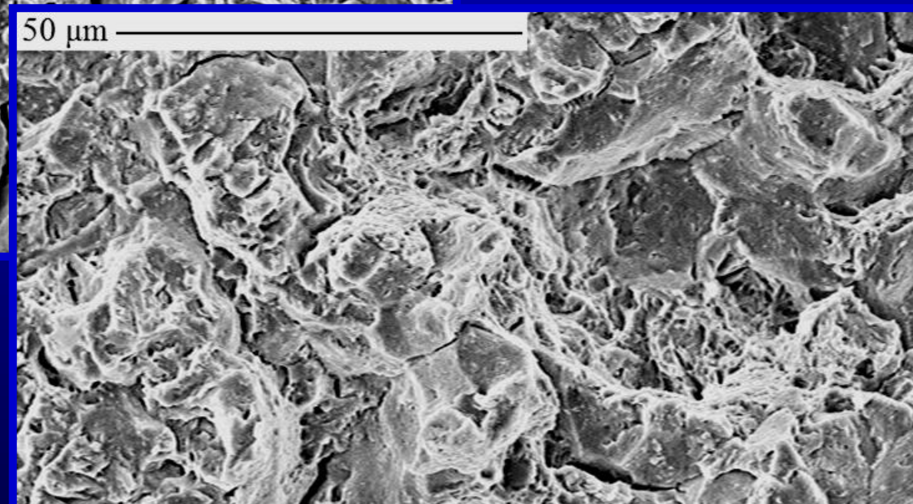
Fractography (V): fatigue tests – overload areas



Surface (~140 mm)
intergranular



Core (~560 mm)
cleavage & ductile



Re-heat-treated (originally ~560 mm)
intergranular (partially ductile)

Fractography (VI): remarks

Macroscopically brittle (overload) fracture mechanisms

- Charpy-V, K_{Ic} and fatigue test specimens with similar microstructures show similar microscopic fracture mechanisms.
- Core and intermediate depth as-received microstructures show cleavage or quasi-cleavage fracture with some ductile areas.
- Both as-received (low depth) and re-heat-treated tempered martensite microstructures show mainly intergranular fracture.

Toughness of tempered martensite microstructures

- Only the re-heat-treated samples show ductile regions at the crack tip of the K_{Ic} specs. (and thus higher toughness).
- Differences in the tempered martensite carbide distribution, not observable by the O.M., must be supposed.

Conclusions (I)

- Mixed microstructures occur throughout the examined bloom.
- The bloom fracture toughness is exceptionally low (about 40 $MPa\sqrt{m}$) for a Q&T steel, considering the achieved UTS.
- The plain-strain fracture prevalently occurs by decohesion, coherently with the fact that, at room temperature, this steel is in its brittle temperature range.
- The low toughness must be attributed to the microstructures caused by the heat treatment, and in turn to the large dimensions of the blooms and of the moulds.
- The much higher toughness of the re-heat-treated samples must be attributed to microstructural differences on a sub-micron scale.

Conclusions (II)

- The rotating bending fatigue endurance limits scale with the tensile strength, rather than with the fracture toughness.
- The endurance limits of the re-heat-treated samples is 25% higher, keeping the differences due to the original location.

- The low fracture toughness is a critical property; the lower fatigue endurance limit allows for a critical crack to develop more rapidly than in a fully Q&T condition.

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Thank you for your attention!