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Development of ultra-high strength seamless pipes for Perforating Guns

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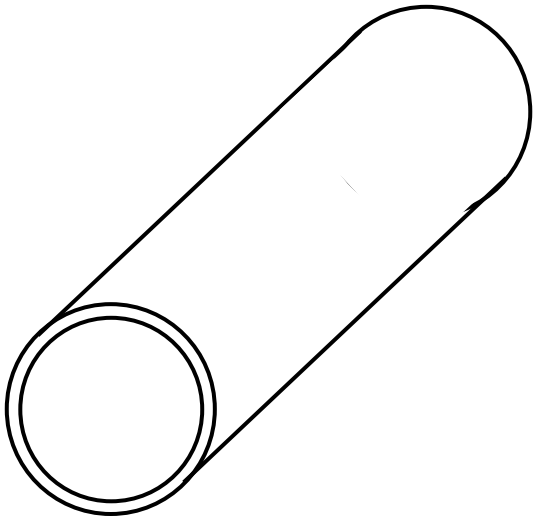
INTRODUCTION

- Pipe for Perforating Gun Carriers (PG) need to sustain during field operation high external hydrostatic pressures and high internal shock loads.
- Increase demand of higher strength to sustain higher collapse loading derive in the need of pipes with Specified Minimum Yield Strength (SMYS) of 165ksi and above.



Typical P110 Tubing:	19800psi
Typical 135ksi Gun Carrier:	24300psi
165ksi Gun Carrier:	29700psi
175ksi Gun Carrier:	31500psi

Outer Diameter: 3.125” – 79.375mm
Nominal Wall: 0.3125” – 7.938mm
Tensile Strength: 2148 kN
Nominal Collapse: 31500psi

INTRODUCTION

- Based on these requirements, steel seamless pipes with good impact toughness and strict dimensional tolerance are required.
- The development of such high strength materials with good toughness is a challenge
- Steel chemistry and processing conditions have to be carefully designed and optimized to achieve these strict requirements.

AGENDA

- Design of steel chemistries for 165ksi and 175ksi based on model calculations.
- Validation with industrial data and fine tuning processing conditions.
- Characterization of materials resulting from industrial trials (microstructure , tempering curve, hardness, tensile and fracture toughness properties).

OBJECTIVE

To develop 165ksi and 175ksi grades with adequate fracture toughness resistance.

	Yield Strength YS (ksi)	Ultimate Tensile Strength UTS (ksi)	Elongation (%)	Impact Toughness Charpy-V Notch CVN (J) Full size specimen
165ksi	165-187	> 170	> 12	> 76
175ksi	175-197	> 180	> 11	> 44

* Test at Room Temperature, Longitudinal Orientation

Metallurgical challenges:

- To meet toughness requirements in this ultra-high strength steels.
- Tempering temperature should be above 450°C to allow for hot straightening operation without introducing residual stresses.

TEMPERING MODEL

Model developed at Tenaris R&D to describe the martensite hardness reduction during tempering. Yield Strength (YS) and Ultimate Tensile Strength (UTS) are derived from hardness prediction, based on empirical relations adjusted for Tenaris steels.

Inputs:

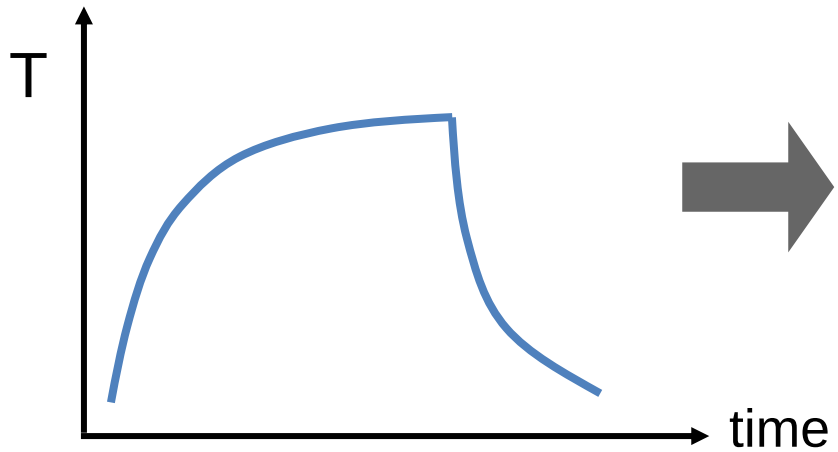
- Steel chemistry
- As quenched hardness
- Thermal cycle: isothermal treatment or user introduced tempering curve (for example a curve calculated with the furnace thermal model).

Outputs:

- Hardness, YS and UTS.

TEMPERING MODEL

A time-temperature equivalent parameter P is used to characterize the tempering curve:



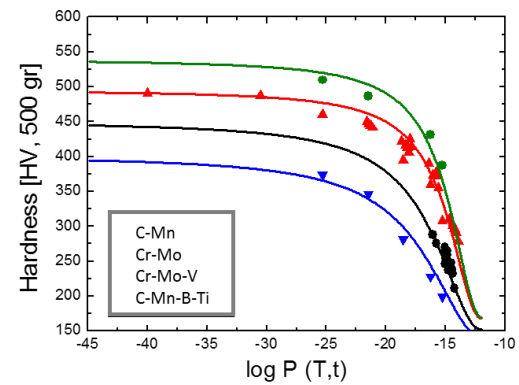
Integral version of the Hollomon-Jaffe parameter:

$$P(T,t) = \int_0^t \exp\left(-\frac{Q}{R \cdot T}\right) \cdot dt$$

The activation energy Q depends on steel chemistry

A mathematical function is used to describe softening during tempering:

$$H(P) = H_0 - \left(H_0 - H_{\min}\right) \cdot \frac{w^2}{\left(\log(P) - \log(P_{\max})\right)^2 + w^2} + \Delta H(\mathrm{V}, P)$$

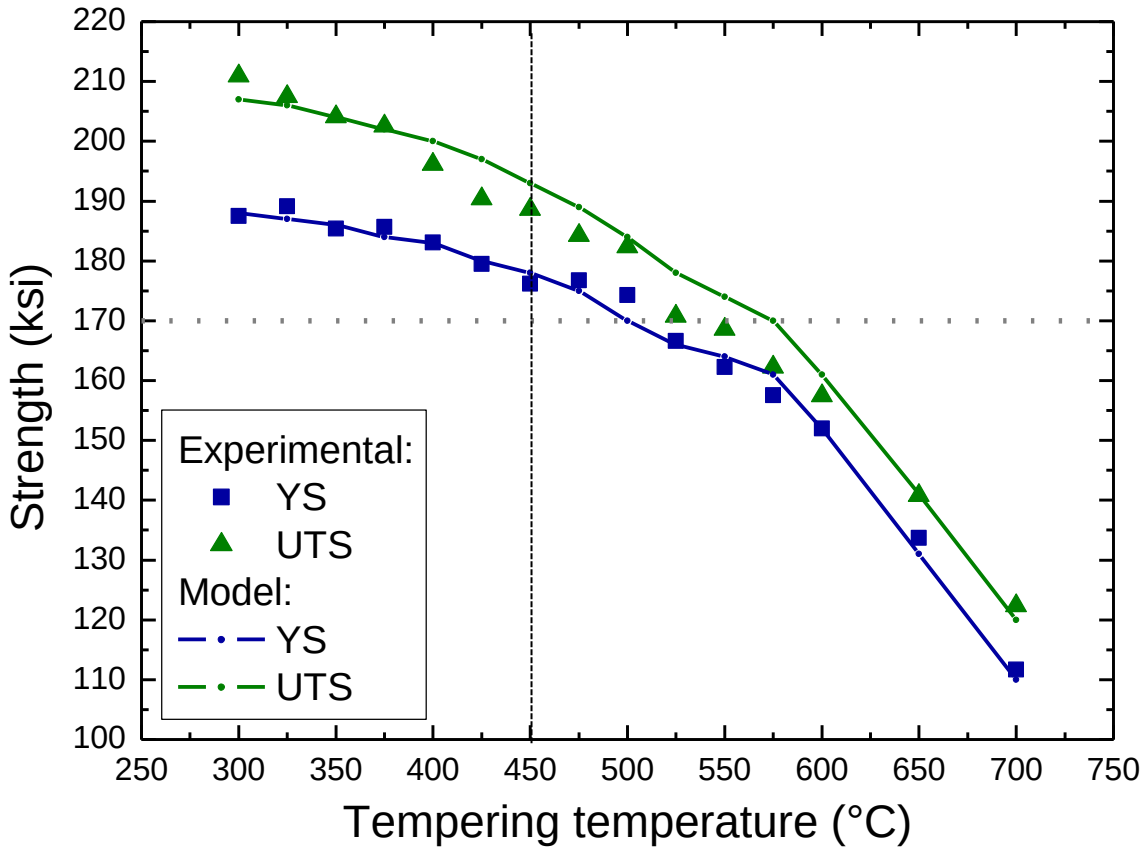


PERFORATING GUN YS > 165 ksi

According to the tempering model and experimental tests, CrMo1 steel used for a 155ksi gun carrier can reach 165 ksi min YS, but tempering temperature is very close to the minimum specified.

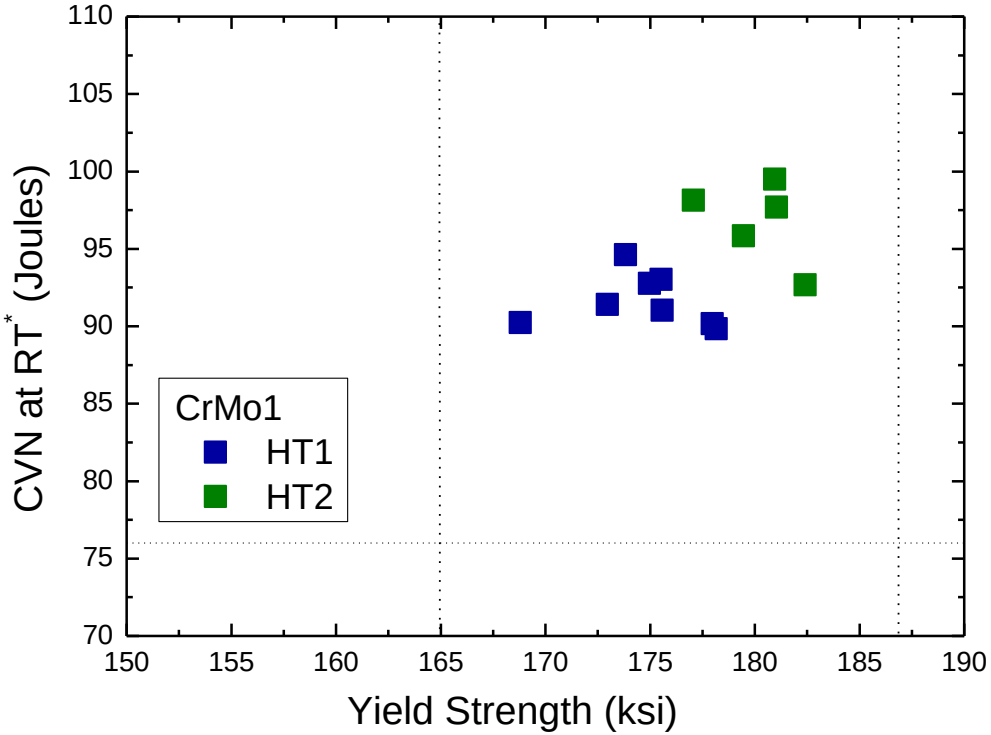
Steel	CrMo1
Tempering model	500°C*

*calculations aiming at YS = 170 ksi performed with tempering model (10-15 minutes soaking time)



PERFORATING GUN YS > 165 ksi

Industrial results for CrMo1 steel:



A modified Heat Treatment (HT) process (HT2) was developed to improve strength-toughness ratio on CrMo1 steel, playing with steel grain refinement. CrMo1 steel with HT2 fulfilled 165ksi specification and final tempering temperature was about 500°C.

PERFORATING GUN YS > 175 ksi

Several chemistries were analyzed with the tempering model. Some examples are shown below:

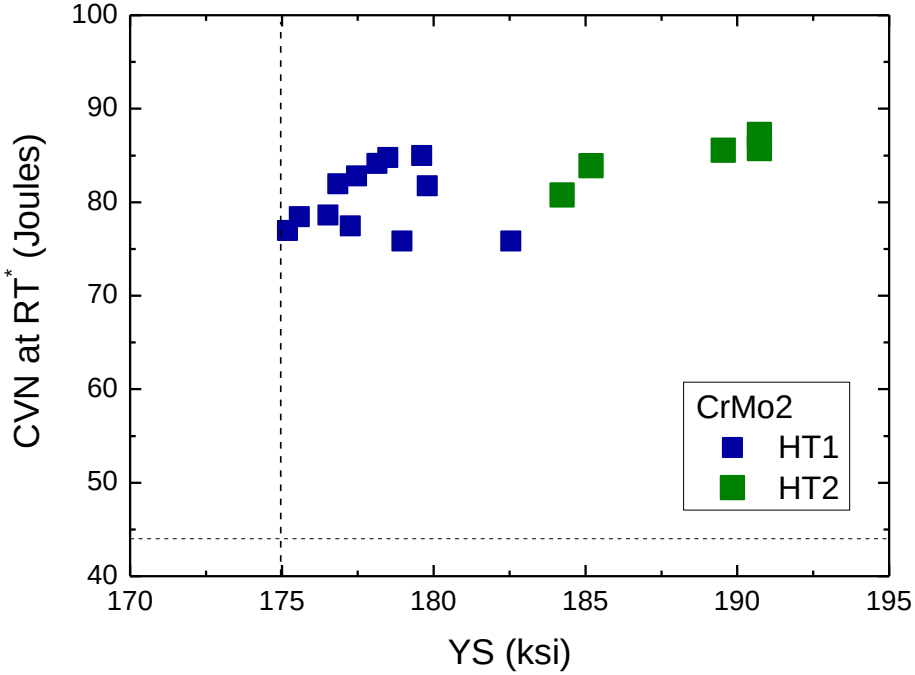
Steel	CrMo1	CrMo2	CrMo3
C (%)	**100**	**100**	**110**
Mn (%)	**100**	**110**	**110**
Si (%)	100	100	100
Cr (%)	**100**	**120**	**150**
Mo (%)	**100**	**140**	**100**
Al (%)	100	100	150
Tempering model	**440°C**	**460°C***	**525°C***

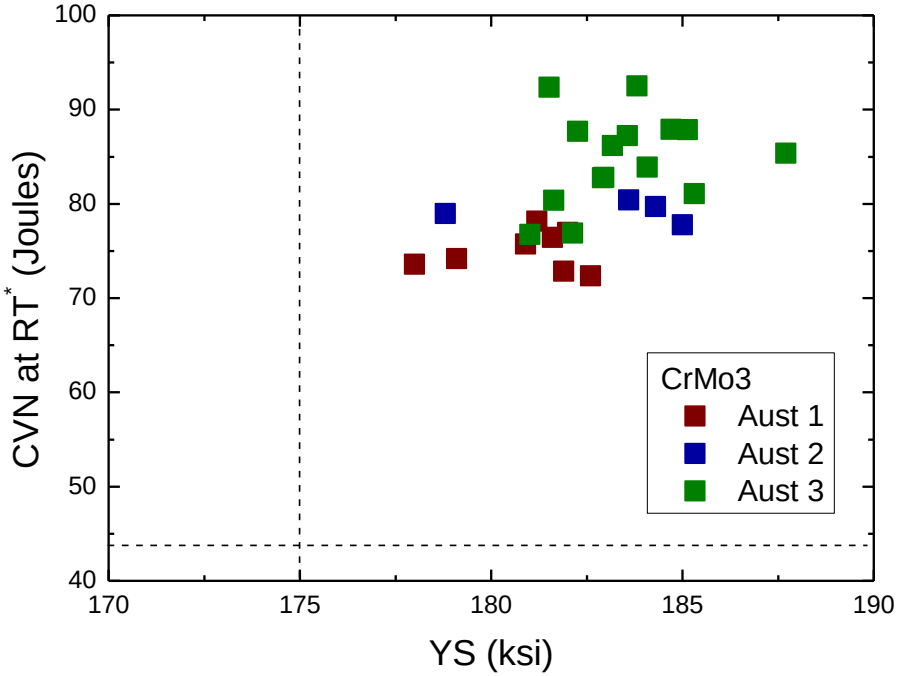
*calculations for single treatment aiming at YS = 180 ksi (10-20 min soaking).

According to these calculations CrMo2 and CrMo3 were suitable chemistries to produce 175ksi.

PERFORATING GUN YS > 175 ksi

Industrial trial results for CrMo2 and CrMo3:





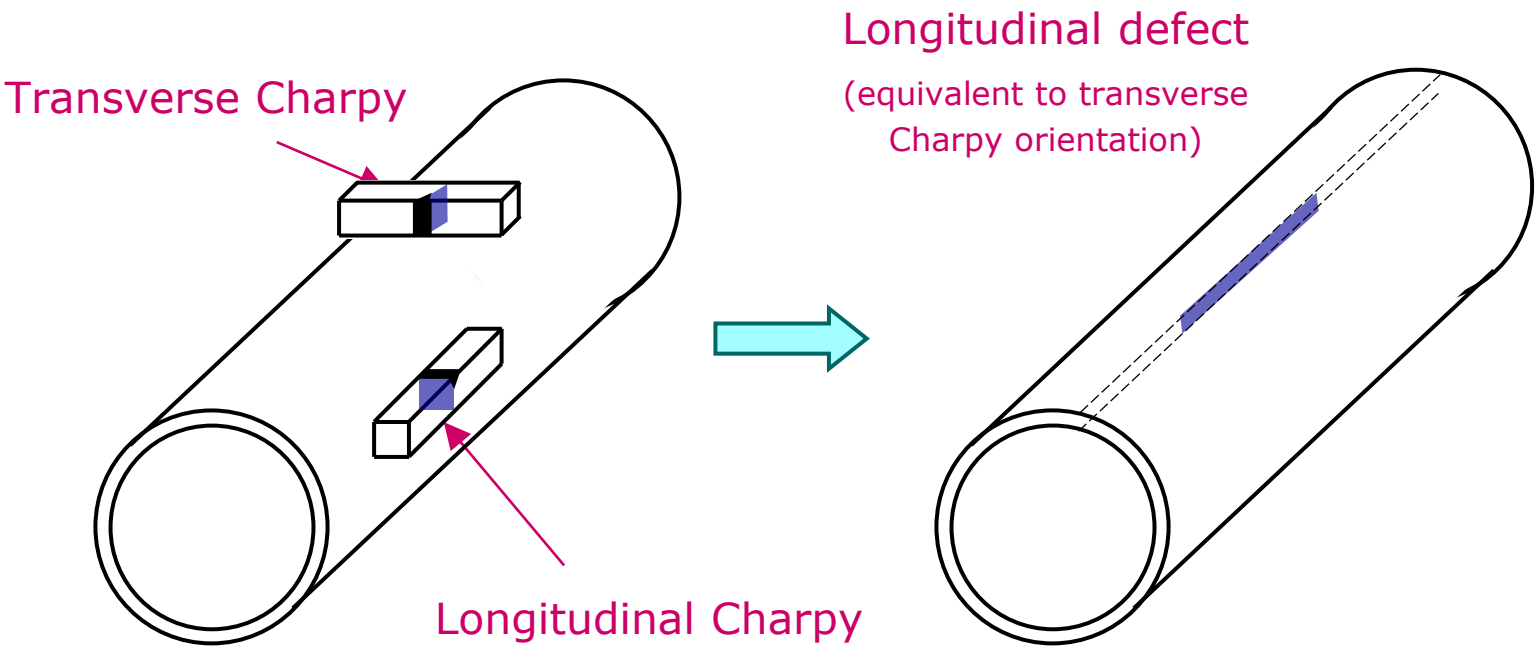
CrMo3 presented slightly better combination of strength-toughness than CrMo2. In both HT2 improved mechanical properties through grain refinement. In CrMo3 steel the modification of austenitization temperature was also useful to improve grain size.

TECHNOLOGICAL TEST FOR PERF GUNS MATERIAL

- Charpy-V Notch Impact values for both 165ksi and 175ksi grades were satisfactorily above minimum requirement
- Nevertheless, especially for small size guns, charpy test in the transversal direction may be difficult or impossible to be performed,
- Furthermore, Charpy-V Notch Impact test results may be not be truly representing the material behavior in dynamic conditions

TECHNOLOGICAL TEST FOR PERF GUNS MATERIAL

Tenaris developed a burst test in pipes with a longitudinal stress concentrator as a way to rank the fracture toughness resistance among different steels.



TECHNOLOGICAL TEST FOR PERF GUNS MATERIAL

- Burst test of Perf Gun material with a longitudinal defect.
  - Defect length equal to the scallop diameter (25mm)
  - Defect mechanized by Electron Discharge Method (EDM), it must be thinner than 1mm
  - Temperature: Room temperature (RT).
  - Loading Rate: lower than 30 MPa/s

The material must complain with:

✓ Minimum pressure requirements

✓ Minimum defect opening / final crack length

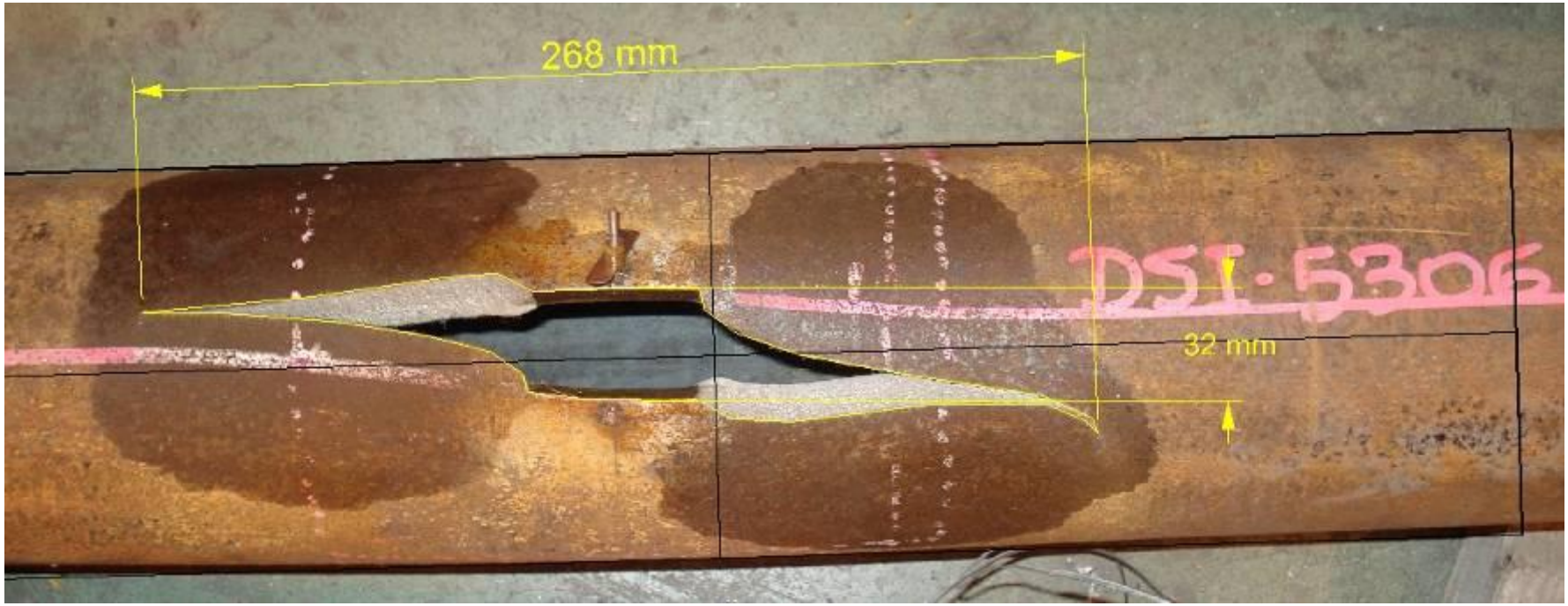
TECHNOLOGICAL TEST FOR PERF GUNS MATERIAL

Significant differences were found between “good” and “bad” materials:

- Good materials: short final crack and high crack mouth opening displacement
- Bad materials: long final crack and low Crack Mouth Opening Displacement (CMOD)

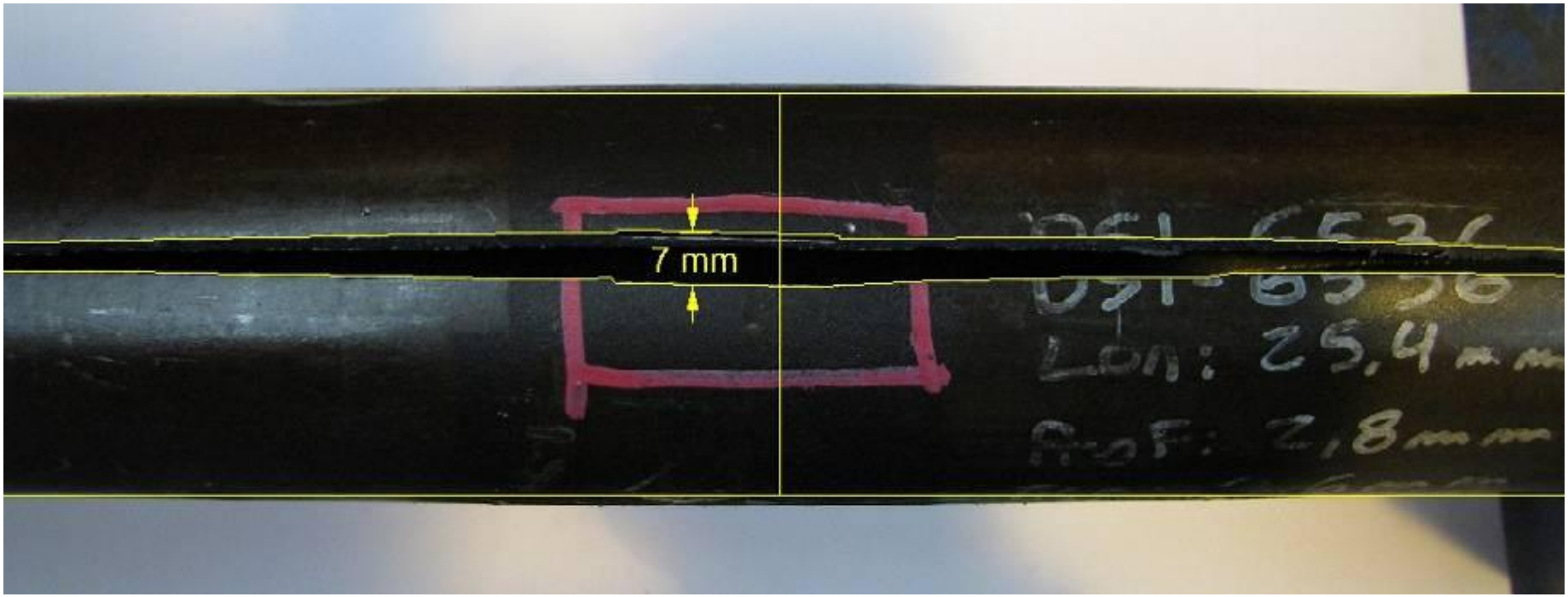
TECHNOLOGICAL TEST FOR PERF GUNS MATERIAL

- "GOOD" Material: High CMOD / final Crack Length ratio



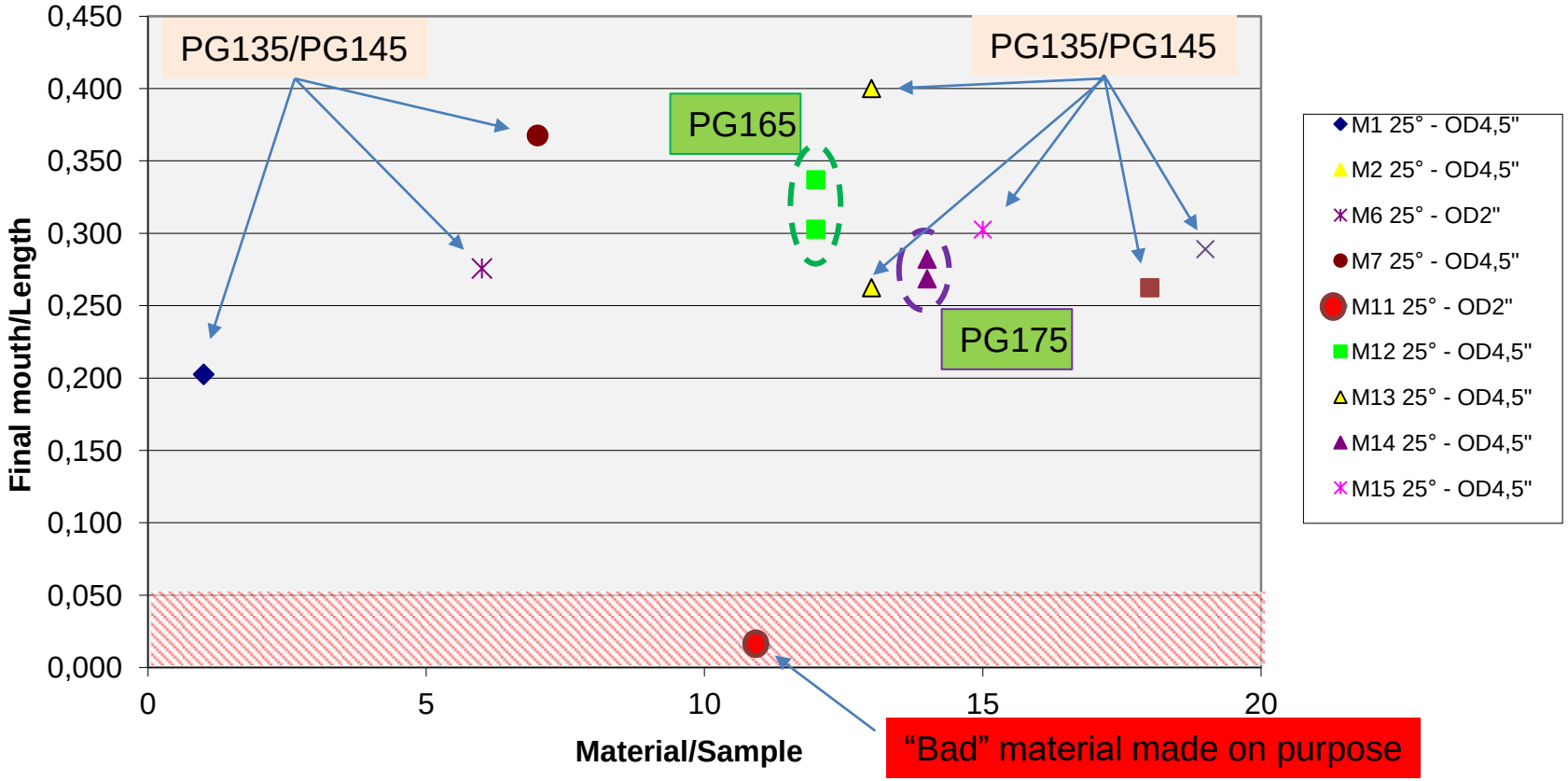
TECHNOLOGICAL TEST FOR PERF GUNS MATERIAL

- "BAD" Material: High CMOD / final Crack Length ratio



TECHNOLOGICAL TEST FOR PERF GUNS MATERIAL

Comparison between High-Strength grades (135/145ksi) and Ultra-High Strength grades (165/175ksi)



CONCLUSIONS

- HT Model calculations helped to design steel chemistries and to make first setting for tempering conditions, to achieve 165ksi and 175ksi min YS
- Mill runs confirmed the targeted tensile-impact properties windows were met, using adequate HT process and matching the required minimum tempering temperatures
- A technological test to evaluate in a simple way the capability of the material to sustain high impact loading was developed.
- In terms of Crack Opening vs. Crack length, the developed 165/175ksi grades are behaving in the same way as the consolidated 135/45ksi grades.
- 165ksi and 175ksi grades have been successfully qualified with field explosive tests (survivability tests) and are now available in the industry

Thank you!

Questions?