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Tenaris

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Development of ultra-high strength seamless pipes for Perforating Guns

INTRODUCTION

- Pipe for Perforating Gun Carriers need to sustain during field operation high external hydrostatic pressures and high internal shock loads.
- Increase demand of higher strength PG to sustain higher collapse loading derive in the need of pipes with SMYS of 165ksi and above.
- 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 PG165 and PG175 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 PG165 and PG175 grades with adequate fracture toughness resistance.

	YS (ksi)	UTS (ksi)	El (%)	CVN (J) Full size specimen
PG165	165-187	> 170	> 12	> 76
PG175	175-197	> 180	> 11	> 44

* Test at RT, 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 Siderca R&D to describe the martensite hardness reduction during tempering. YS and UTS are derived from hardness prediction, based on empirical relations adjusted for Siderca steels.

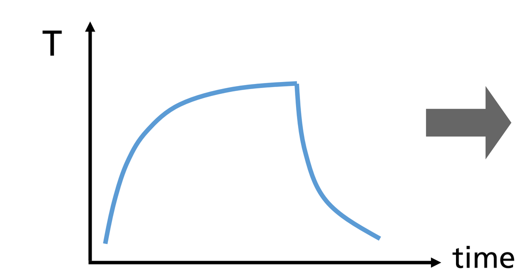
Inputs:

- Steel chemistry (C, Mn, Si, Cr, Mo, Ni and V).
- As quenched hardness (if it is not known the model assumes an initial hardness calculated for 100% martensite).
- Thermal cycle: isothermal treatment or user introduced tempering curve (for example a curve calculated with the furnace thermal model).

Outputs:

- Hardness, YS and UTS.

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



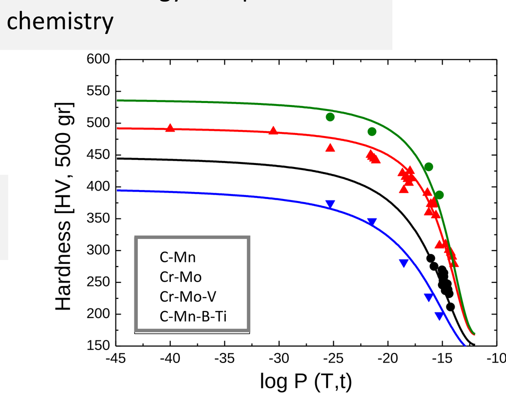
Integral version of the Hollomon-Jaffe parameter:

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

The activation energy Q depends on steel chemistry

A mathematical function is used to describe softening during tempering:

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

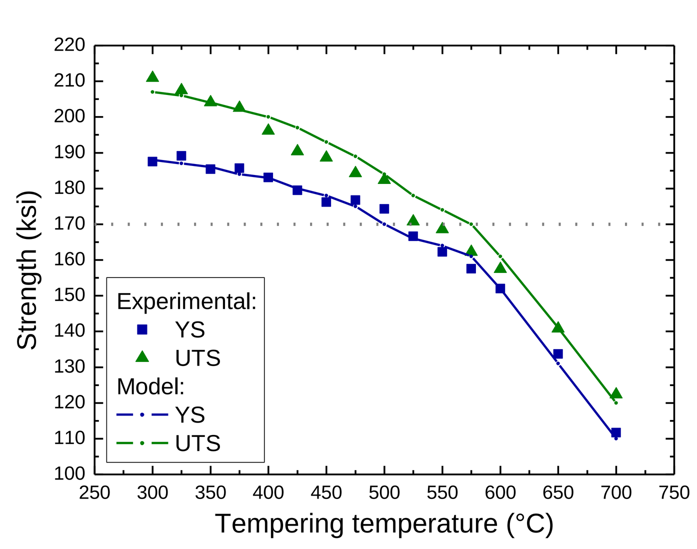


PERFORATING GUN YS > 165 ksi

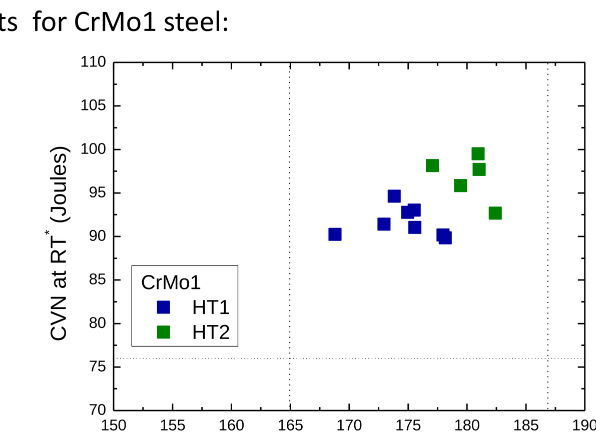
According to the tempering model, CrMo1 steel used for PG155 can reach PG165 when tempering near the minimum specified. The model prediction was validated by lab heat treatments.

Steel	CrMo1
Tempering model	500°C*

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



Industrial results for CrMo1 steel:



* Charpy V-notch measured on samples subsize (10mm x 7.5 mm, LC). Values proportionally converted to fullsize.

CrMo1 steel with HT1 fulfilled PG165 specifications with DBTT = -30°C. There was an improvement in strength-toughness when performing a modified heat treatment (HT2) due to grain refinement.

PERFORATING GUN YS > 175 ksi

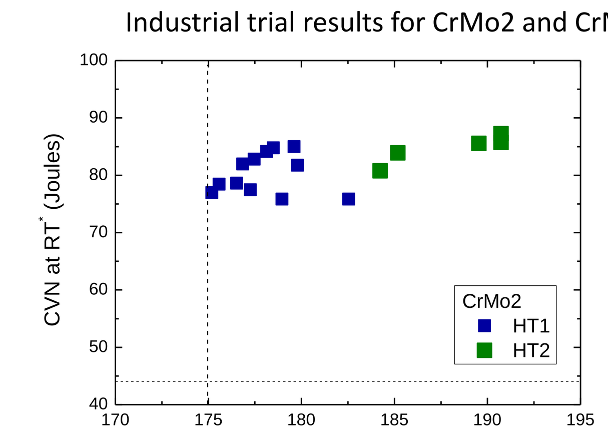
Several chemistries were analyzed with the tempering model. Some examples are shown below:

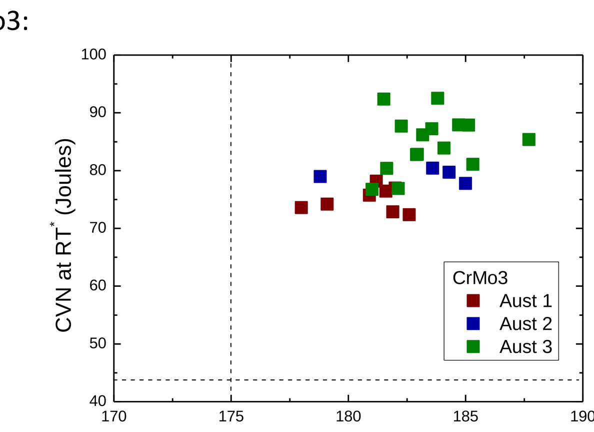
Steel	CrMo1	CrMo2	CrMo3
C (%)	100	100	110
Mn (%)	100	110	110
Si (%)	100	100	100
Cr (%)	100	120	150
Mo (%)	100	140	100
Al (%)	100	100	150
Tempering model	440°C	460°C*	525°C*

*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 PG175.

Industrial trial results for CrMo2 and CrMo3:





* Charpy V-notch measured on subsize samples (10 mm x 7.5 mm, LC), values proportionally converted to fullsize.

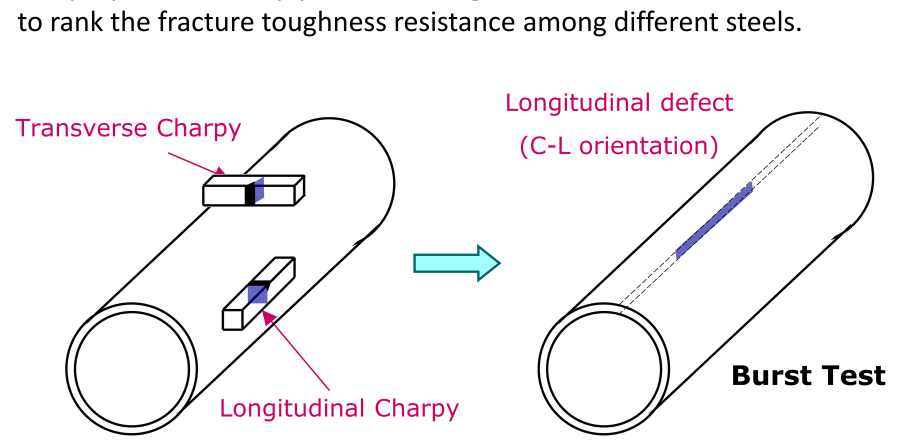
CrMo3 presented slightly better combination of strength-toughness than CrMo2. In both HT2 improved mechanical properties through grain refinement. In CrMo3 steel the modification of austenitization temperature was also useful to decrease grain size.

Technological Test for Perforating Gun Materials

The toughness of material for PG applications is characterized by Charpy impact tests

> Specimens are difficult to obtain from small size pipes

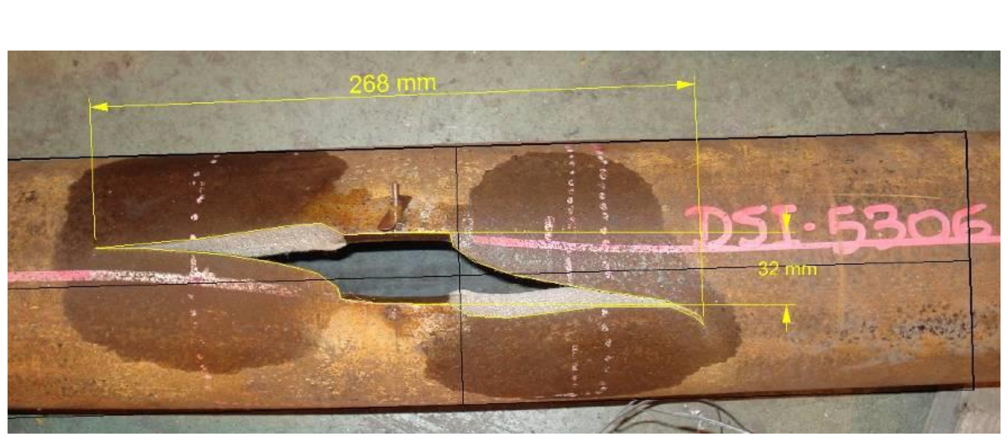
> It is proposed to test pipes with a longitudinal stress concentrator as a way to rank the fracture toughness resistance among different steels.



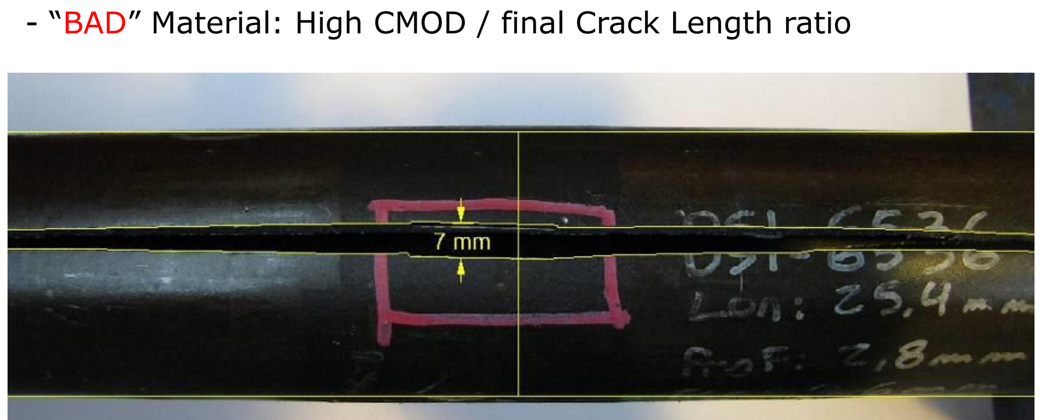
Significant differences were found between "good" and "bad" materials:

- Good materials: short final crack and high crack mouth opening displacement
- Bad materials: long final crack and low crack mouth opening displacement

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



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



Conclusions

- In mill trials the objective PG175 tensile-impact properties were met with CrMo3 steel tempered at above 500°C and adequate heat treatments.
- In comparison with CrMo1, CrMo3 steel presented a slightly reduced toughness for similar strength levels. However, this steel allowed to reach aimed YS values without tempering below 500°C, with the subsequent increase in temperature during straightening operation.
- Model calculations helped to design steel chemistries and to make first setting for tempering conditions.
- A technological test to evaluate in a simple way the capability of the material to sustain high impact loading was developed.