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.

<table>
<thead>
<tr>
<th>YS (ksi)</th>
<th>UTS (ksi)</th>
<th>Si (%)</th>
<th>Full size specimens</th>
</tr>
</thead>
<tbody>
<tr>
<td>PG165</td>
<td>170</td>
<td>&gt; 250</td>
<td>&gt; 11</td>
</tr>
<tr>
<td>PG175</td>
<td>175</td>
<td>&gt; 250</td>
<td>&gt; 11</td>
</tr>
</tbody>
</table>

Metallographic 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 Silberia R&D to describe the martensite hardness reduction during tempering. YS and UTS are derived from hardness prediction, based on empirical relations adjusted for Silberia steels.

Inputs:

• Steel chemistry (C, Si, Cr, Mo, Mn, 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.

According to these calculations CrMo2 and CrMo3 were suitable chemistries to produce PG175.

PERFORATING GUN YS > 165 ksi

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

<table>
<thead>
<tr>
<th>Steel</th>
<th>CrMo (ksi)</th>
<th>CrMo2 (ksi)</th>
<th>CrMo3 (ksi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C (%)</td>
<td>0.10</td>
<td>0.10</td>
<td>0.10</td>
</tr>
<tr>
<td>Si (%)</td>
<td>0.15</td>
<td>0.15</td>
<td>0.15</td>
</tr>
<tr>
<td>Mn (%)</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
</tr>
<tr>
<td>Mo (%)</td>
<td>0.50</td>
<td>0.50</td>
<td>0.50</td>
</tr>
<tr>
<td>Heat</td>
<td>200</td>
<td>200</td>
<td>200</td>
</tr>
<tr>
<td>Tempering</td>
<td>1000</td>
<td>1000</td>
<td>1000</td>
</tr>
<tr>
<td><strong>CrMo3</strong></td>
<td>440°C</td>
<td>460°C</td>
<td>520°C</td>
</tr>
</tbody>
</table>

According to these calculations CrMo2 and CrMo3 were suitable chemistries to produce PG175.

PERFORATING GUN YS > 175 ksi

Industrial trial results for CrMo3:

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.

Technological Test for Perforating Gun Materials

**“GOOD”** Material: High CHOD / final Crack Length ratio

**“BAD”** Material: Low CHOD / 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 CrMo4, 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.