ADVANCED HIGH STRENGTH STEELS FOR FORGING APPLICATIONS

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1. Design process for steel innovation

2. Example of development with partnership
   A micro-alloyed medium carbon steel grade for heavy duty crankshafts

3. Examples of innovative development to prepare the future
   A medium carbon steel grade with acicular ferrite microstructure
   A low carbon bainitic steel grade with improved toughness
OBJECTIVES OF DESIGN PROCESS

TO PROPOSE THE BEST STEEL GRADE, TAKING INTO CONSIDERATION

THE TECHNICAL NEEDS

- to achieve the required properties of the finished part  
  *(improvement of the properties and/or weight saving of parts)*
- to be compatible with the process of the steel producer
- to be adapted to the constraints of the processes of the customers

THE ECONOMICAL CONSTRAINTS

- to obtain a finished part at a cost which satisfies all parties concerned
- to save energy by removing heat treatment

THE ENVIRONMENTAL EXPECTATIONS

- to reduce the environmental impact of all the manufacturing chain
DESIGN PROCESS

Commercial production

Participation to the approval process

Quality evaluation of the forged parts
  Assistance to the customers

Quality evaluation of the bars

Industrial heat

Process development and trials

Verification of the design by the workshop

Laboratory investigations

Cast and forge lab ingots
  With new chemistries

Customers needs & expectations
  OEM, tier 1, tier 2

Collect initial data
  Benchmarking
  Functional analysis
  Processing
  Environmental constraints & regulations
  COST/PROFITABILITY

Establish a partnership
  Workshop

Define the requirements of the part
  Heat treatments, machinability, fatigue

Define the properties of the steel
  YS, TS Toughness, Jominy, microstructure, cleanliness

Define the steel grade
  Data base
  know how
  computer modelling

Evaluate the feasibility of the project

Participation to the approval process

Quality evaluation of the forged parts

Quality evaluation of the bars

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A micro alloyed medium carbon grade for heavy duty crankshafts

A successful partnership between THYSSEN KRUPP AUTOMOTIVE and MITTAL STEEL
INDUSTRIAL AIM

The Project Team:
The 1st tier supplier for automotive industry: ThyssenKrupp Mavilor
The 2nd tier supplier or forging partner: ThyssenKrupp Gerlach
The 3rd tier supplier or steel production company: Mittal Steel Ruhrort
Mittal Steel Europe R&D

To develop a heavy duty crankshaft
• with high torsional fatigue strength
• as forged (without bulk heat treatment after forging)

With better mechanical properties than the actual crankshafts
(C38N2 or 38MnSiV6) (TS>1000MPa, fatigue bending, torsional fatigue)

With properties equivalent to a quenched and tempered grade (34CrNiMo6)
(machinability, deep drilling, induction hardening without cracks)

With a price of the finished crankshaft lower than with steel grade 34CrNiMo6
LABORATORY INVESTIGATIONS

1. To characterise the forging process especially the cooling
2. To conceive the steel grade chemistry
3. To cast laboratory ingots with different steel chemistries
4. To study the phases transformation  -- > Select chemistries
5. To test the aptitude of the new grade to be forged
6. To simulate the cooling of the crankshaft on bar samples
7. To carry out the induction hardening treatment
8. To characterise the machinability
9. To perform the mechanical tests and fatigue tests on samples

After that, parts are forged, machined and tested
Temperature measurements on a heavy duty crankshaft

Cooling from 1100-1150°C

Temperature measurements on bars forged from Ingots

Cooling from 1100-1150°C

A cooling chamber was set up to reproduce the cooling rate of the crankshaft on bars.
Laboratory simulation treatment

- Core of the bar
- Core of the crankshaft
- Subsurface of the bar
- Subsurface of the crankshaft

Temperature (°C) vs. Time (h:min:s)
Ingots: 30 to 40 kg, 120x120 (mm²)
MACHINABILITY TEST

STANDARD MATHON TEST

D350 = 19 mm
D350 = 30 mm
## RESULTS ON DIFFERENT GRADES

<table>
<thead>
<tr>
<th>Grade</th>
<th>HV30</th>
<th>TS MPa</th>
<th>YS MPa</th>
<th>EI %</th>
<th>RA %</th>
<th>Microstructure</th>
<th>D350 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>C38+N2 (ind)</td>
<td>250</td>
<td>800</td>
<td>470</td>
<td>17</td>
<td>55</td>
<td>Ferrite+Pearlite</td>
<td>31</td>
</tr>
<tr>
<td>34CrNiMo6 (ind)</td>
<td>320</td>
<td>1020</td>
<td>900</td>
<td>16</td>
<td>56</td>
<td>Tempered Martensite</td>
<td>13</td>
</tr>
<tr>
<td>HEAT A (lab)</td>
<td>345</td>
<td>1080</td>
<td>710</td>
<td>17</td>
<td>35</td>
<td>Bainite+Pearlite</td>
<td>30</td>
</tr>
<tr>
<td>HEAT B (lab)</td>
<td>270</td>
<td>890</td>
<td>535</td>
<td>18</td>
<td>47</td>
<td>Pearlite+Ferrite</td>
<td>25</td>
</tr>
<tr>
<td>HEAT C (lab)</td>
<td>340</td>
<td>1180</td>
<td>685</td>
<td>18</td>
<td>33</td>
<td>Bainite</td>
<td>9</td>
</tr>
</tbody>
</table>

![HEAT A](image1.png)  ![HEAT B](image2.png)  ![HEAT C](image3.png)
INDUSTRIAL HEAT

Best compromise mechanical properties/machinability
-> the laboratory heat A

An industrial heat was cast at MITTAL STEEL RUHRORT based on the same chemistry -> CRIE A7

<table>
<thead>
<tr>
<th>Grades</th>
<th>TS MPa</th>
<th>YS MPa</th>
<th>El %</th>
<th>RA %</th>
<th>Hv30</th>
<th>Structure</th>
<th>Mathon D350mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>CRIE A7 INDUSTRIAL HEAT</td>
<td>1195</td>
<td>735</td>
<td>13</td>
<td>17</td>
<td>350</td>
<td>B + 10% P</td>
<td>9</td>
</tr>
</tbody>
</table>
The industrial grade CRIE A7 having promising mechanical properties, the project team decided to forge 2 kinds of heavy duty crankshafts. C1 and C2 were forged at ThyssenKrupp.
<table>
<thead>
<tr>
<th>Grades</th>
<th>TS MPa</th>
<th>YS MPa</th>
<th>El %</th>
<th>RA %</th>
<th>Hardness Hv30</th>
<th>Structure</th>
<th>Mathon D350</th>
</tr>
</thead>
<tbody>
<tr>
<td>CRIE A7 Crankshaft C1</td>
<td>1206</td>
<td>829</td>
<td>13</td>
<td>18</td>
<td>300 - 345</td>
<td>B + P (variable %)</td>
<td>13 - 20</td>
</tr>
<tr>
<td>CRIE A7 Crankshaft C2</td>
<td>1188</td>
<td>720</td>
<td>17</td>
<td>21</td>
<td>340-375</td>
<td>B + P (variable %)</td>
<td>9</td>
</tr>
<tr>
<td>34CrNiMo6</td>
<td>1020</td>
<td>900</td>
<td>16</td>
<td>56</td>
<td>320</td>
<td>Tempered Martensite</td>
<td>13</td>
</tr>
</tbody>
</table>
The CRIEA7 structure can meet the machinability requirements on condition of using the suitable parameters for machining.
Tests are performed on standard samples taken from forged parts.
FATIGUE RESULTS

STANDARD SAMPLES FROM CRANKSHAFTS

The rotative bending fatigue tests performed show good fatigue properties of the steel grade CRIE A7

TESTS ON CRANKSHAFTS

Bending fatigue tests are satisfying.

The torsional fatigue tests are in progress at ThyssenKrupp MAVILOR: the first results are good
A LARGE STEP TOWARDS HIGH STRENGTH

* Properties measured on finished parts

TS (MPa)

900
850
800
750
700
650
600
550
500
450
700 750 800 850 900 950 1000 1050 1100 1150 1200 1250 1300

YS (MPa)

F+P
38MnSi V 5/6
=C38 mod*

F+P
38MnSi6+N2
=C38N2*

Q+T Ma
34CrNiMo6*

B+P or B
CRIEA7
=MCBS*

Spec area

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Thanks to this successful partnership between a steel producer (Mittal Steel) and steel transformers (ThyssenKrupp Automotive companies) …

A new micro alloyed grade CRIE A7 has been developed for heavy duty crankshafts. It’s a medium carbon bainitic steel (MCBS). It has a mixed Bainite+ Pearlite microstructure and a TS superior to 1100 MPa which gives it a good fatigue behaviour.
INNOVATIVE DEVELOPMENTS

Aim: High Strength without losing toughness

Usually
TS /---> Toughness \n
YS (MPa)

TS (MPa)

F+P
38MnSiV5-6
Innovative development with University collaboration
Nancy School of Mines
AF MORPHOLOGY

- Fine
- Irregular
- Autocatalytic

[Image of metal morphology with a scale of 2 μm]
AF GERMINATION MECHANISM

DIAGRAM

- Acicular ferrite
- $\gamma$ ferrite
- Idiomorphic ferrite
- Pearlite
- Martensite
- Allotriomorphic ferrite
- $\gamma$ grain boundary
- Disoriented ferrite laths
- Inter laths spaces
- Non-metallic inclusions

SEM PHOTOGRAPH

Scale: 10 μm
<table>
<thead>
<tr>
<th>PROPERTIES</th>
<th>FA1</th>
<th>FA2</th>
<th>FA3</th>
<th>FA4</th>
<th>38MnSiV6</th>
</tr>
</thead>
<tbody>
<tr>
<td>STRUCTURE</td>
<td>F+P(30%FA)</td>
<td>&gt;90%</td>
<td>&gt;90%</td>
<td>&gt;80%</td>
<td>F+P</td>
</tr>
<tr>
<td>TS Mpa</td>
<td>980</td>
<td>1008</td>
<td>1023</td>
<td>1106</td>
<td>860</td>
</tr>
<tr>
<td>YS Mpa</td>
<td>696</td>
<td>665</td>
<td>678</td>
<td>682</td>
<td>595</td>
</tr>
<tr>
<td>El %</td>
<td>17</td>
<td>21</td>
<td>21</td>
<td>20</td>
<td>17</td>
</tr>
<tr>
<td>RA %</td>
<td>53</td>
<td>35</td>
<td>37</td>
<td>35</td>
<td>40</td>
</tr>
<tr>
<td>Toughness 20°C (KU358) (J/cm²)</td>
<td>45</td>
<td>45</td>
<td>39</td>
<td>50</td>
<td>36</td>
</tr>
<tr>
<td>HARDNESS HV1 or HV30</td>
<td>288</td>
<td>290</td>
<td>295</td>
<td>300</td>
<td>258</td>
</tr>
</tbody>
</table>
Objectives: High strength, high toughness

Given by: Bainitic microstructure with Nb additions, low carbon

Originally the low carbon Bainitic grades (named Freeform) were developed by MITTAL STEEL USA for cold heading applications without any heat treatment

(PATENT filed in 1996)

New Grades developed with similar microstructures

For hot forging applications -> Freeform™ DQ (Direct Quenched)
FREEFORM™ DQ FOR HOT FORGING

Target: To obtain parts by hot forging and direct quenching without tempering.
FREEFORM™ DQ - FORGING TRIALS

EXTRUSION

UPSETTING

AXLE SHAPE
**FREEFORM™ DQ/QUENCHABILITY**

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### Freeform™ DQ 50mm Water quenched

<table>
<thead>
<tr>
<th>Structures</th>
<th>SURFACE</th>
<th>12 mm depth</th>
<th>CENTER</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>MECHANICAL PROPERTIES</th>
<th>TS MPa</th>
<th>YS MPa</th>
<th>El %</th>
<th>RA %</th>
<th>KU</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1200</td>
<td>975</td>
<td>16</td>
<td>72</td>
<td>20 °C</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>100 J/cm²</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>- 40 °C</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>40 J/cm²</td>
</tr>
</tbody>
</table>

| HARDNESS (Hv₃₀) | Mini : 375 Hv₃₀ | Maxi : 406 Hv₃₀ |

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Freeform™ DQ is well adapted to the manufacture, by hot forging and direct quenching, of components demanding a combination of high strength, ductility and toughness.

<table>
<thead>
<tr>
<th>GRADES &amp; HEAT TREATMENT</th>
<th>TS MPa</th>
<th>YS MPa</th>
<th>El %</th>
<th>RA %</th>
<th>KU J/cm² 20°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>FREEFORM DQ</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>WATER 40mm</td>
<td>1200</td>
<td>980</td>
<td>14</td>
<td>73</td>
<td>95</td>
</tr>
<tr>
<td>WATER 50mm</td>
<td>1200</td>
<td>975</td>
<td>16</td>
<td>72</td>
<td>100</td>
</tr>
<tr>
<td>OIL 40mm</td>
<td>1050</td>
<td>925</td>
<td>14</td>
<td>76</td>
<td>140</td>
</tr>
<tr>
<td>OIL 50mm</td>
<td>1040</td>
<td>915</td>
<td>16</td>
<td>74</td>
<td>110</td>
</tr>
<tr>
<td>42CrMo4</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>QUENCHED &amp; TEMPERED</td>
<td>1200</td>
<td>1100</td>
<td>14</td>
<td>55</td>
<td>55</td>
</tr>
</tbody>
</table>

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HIGH STRENGTH STEELS FOR FORGING MARKET

- FPS 38MnSiV6
- AFS
- LCBS
- MCBS
- 42CrMo4

Young's Modulus (YS) vs. Tensile Strength (TS) graph.
Forging ahead, TOGETHER, we are shaping the future of steel products