Mooring Integrity: Forensics Programs on Used Mooring Connectors
Lessons Learned, Present Practices & Future Developments

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Abstract

Paper is based on the results obtained from various forensics joint study programs (latest finalized in August 2014) conducted in between Mooring Connectors Manufacturer, EPCI Contractors & Operators of the Floating Production Units.

The used forged mooring components analyzed in this program have been installed successfully in West Africa, North Sea and Asia for at least 10+ years. All have passed their lifetime with success and hence have been replaced (some after 20+ years of operation). The test program conducted by the parties has been focusing on:

- Dimensional controls and comparison with as-built data
- Mechanical tests as per today’s class standard (IACS W22 standard or equivalent)
- Real size proof load and break load tests of the old connectors when possible
- Chemical and various additional studies

If all the products have been performing as expected while installed offshore, some present some serious deviations from standards which were not identified during manufacturing process and control. The behavior of the products observed in this study can be considered as a good indication of the general performances of products supplied by the industry a decade ago and more. This obviously raises questions about the integrity of many aging mooring systems around the world. It is also a good opportunity to compare standard rules recommendations and real operation conditions and recalibrate the model if required. (Corrosion allowance criteria for instance).

To complete the analysis, similar mooring connectors have been produced again in 2013 & 2014 by the same manufacturer. The comparison of the results obtained at a 10+ year gap give a good indication of the progress of the industry and concentrate the lessons learned for a reliable operation of mooring connectors.
# Table of Contents

Abstract ............................................................................................................................................................... 1 
Table of Contents ................................................................................................................................................ 2 
Introduction......................................................................................................................................................... 3 

I. Long term mooring connection mission ...................................................................................................... 4

II. Results from Forensics .................................................................................................................................. 5
  1. Conditions of the tests ............................................................................................................................ 5
  2. Tests performed on end joining shackles DN120mm R4 ...................................................................... 5
     a) Visual check and dimensional control ................................................................................................. 5
     b) Break Load Test ................................................................................................................................... 7
     c) Mechanical Tests & Comparison with 2014 production ...................................................................... 8
  3. Tests performed on triplates for chain DN95mm R4 .............................................................................. 9
     a) Visual check and dimensional control ................................................................................................. 9
     b) Break load test ..................................................................................................................................... 9
     c) Mechanical Tests & Comparison with 2014 production ...................................................................... 9
  4. Tests performed on open socket for cable Ø110mm ............................................................................ 10
     a) Visual check and dimensional control ............................................................................................... 10
     b) Break load test ................................................................................................................................... 10
     c) Mechanical Tests & Comparison with 2013 production ................................................................... 10
  5. Summary of the forensics results observed .......................................................................................... 10

III. How could it happen? ............................................................................................................................ 11
  1. Relevancy of the tests performed on the connectors ........................................................................... 11
  2. Gap in the specifications ....................................................................................................................... 13
  3. Summary of section ............................................................................................................................... 13

IV. Results Analysis / Key factors in connectors manufacturing ................................................................. 14
  1. Raw material quality impact .................................................................................................................. 14
  2. Heat treatment accuracy impact ........................................................................................................... 15

V. Lessons Learned & Future Challenges ....................................................................................................... 20
  1. Lessons learned ..................................................................................................................................... 20
  2. Future Challenges .................................................................................................................................. 21

References ......................................................................................................................................................... 22
Introduction

According to a technical study performed and presented by Mr. Kai-tung Ma (Chevron ETC) at OTC 2013 [1], more than 20 issues with long term mooring lines have been officially listed for the 2001-2011 period. An “issue” can be a mooring system damage (only one line impacted, no direct consequence to production) or a mooring system failure (two or more lines impacted, causing production shut down and potentially damages to riser system). A long term mooring system is defined as a “permanent system”, hence a system designed to hold a floating production unit in position (contrary to temporary mooring systems used for instance for drilling units). This paper is fousing on long term mooring forged connectors.

Root causes identified include improper engineering and weather conditions assessment at design stage, manufacturing defect, fatigue failure, corrosion, improper installation of material and improper use.

In term of frequency of failure, the following ranking can be established independently of the root causes:

1. Chain comes as first cause of failure, with 50% of the cases
2. Connectors comes second (23% of issues reported)
3. Wire rope represent 19% of issues, making it the third cause of mooring failure
4. Fiber represents only 8% of failures reported and monitored.

If the above ranking is tuned to assess the risk of failure per meter of mooring line, the ranking is modified as connectors will then take the first place. Interfaces in between the different elements of the mooring lines – regardless of the line composition – are likely to be the area of weak points as they concentrate changes in geometry, important fluctuations in term of linear weight, variation of stiffness...

For the last 20 years, more than 150 mooring lines have been replaced (due to issue or as preventive action). (OTC 2013 Paper, Mr. Sai Mahji, KBR) [2] & [3]. Mooring integrity is becoming a key issue for majors, and more and more of them are considering emergency plans from their existing assets and new projects (TOTAL Company for instance with the Emergency Pipeline and Subsea Repair System (EPSRS program), allowing a complete spare mooring line to be available in case of issue).

Le Beon Manufacturing has been providing forged mooring connectors to the Offshore industry for 30+ years and is certified by class societies for this application. Involved in various JIPs, company is also performing forensics program with majors and engineerings at the end of project lifetime to assess the conditions of connectors and compare it with expectations.

In this context, some of the results obtained recently on connectors from decommissioned mooring lines around the world are in deviation with current offshore standard. This obviously raise questions:

- Why these deviations were not identified during initial production?
- How is the industry addressing these challenges?
- How serious these deviations are? How to assess the exact risk potentially generated?
I. Long term mooring connection mission

Before looking at the details of the results of forensics programs, it is necessary to understand which are the key parameters and factors to be considered for connectors assessment.

Connectors are designed to perform an interface in between various segments of a mooring line, and they should—at least—comply with the following targets:

- Performing the connection with the various elements (pile or anchor pad eye, chain, wire rope, polyester, hull) without interferences and without impacting surrounding elements performances
- Matching or exceeding the performances of the other elements of the line in order not to be the weak link of the mooring system:
  - In term of strength
  - In term of lifetime capacity
  - In term of fatigue capacity
- Being compatible in term of material homogeneity with other elements of the mooring line to prevent corrosion.

The applicable standards of the industry are the IACS W22 [4] and the API 2F [5]. From these general standards (IACS especially for long term mooring application, the aim of our study here), every class societies is then issuing a dedicated standard, but the global philosophy is similar from a class to another. It is interesting to look briefly at the evolution of these standards since 15 or 20 years to understand the progresses of industry and how some of the challenges have been mitigated.
II. Results from Forensics

1. Conditions of the tests

Through different forensics programs performed recently, LBM has been in a position to recover old connectors de-commissioned from different fields worldwide. The results presented below are extracted from the studies performed and have been selected due to their interests in representing some of the industry most common issues. Three type of products are considered: Shackle, Socket & Triplate.

Our forensics partners have expressed the wish to keep the data anonymous and not field identified. No additional information regarding these results will be provided and are property of LBM & involved parties.

The general process has been the same for the various products received:

- Identification of the available pieces (number, marking areas)
- Photographs of areas of interest regarding corrosion, dimensional integrity and readability of markings.
- Dimensional inspection and comparison with the as built dimensional inspection reports.
- Proof Load and Break Load testing of one product when quantity so allowed (“worst case” regarding dimensional inspection). Loads have been calculated regarding the diameter of corroded chain with 0.4mm/year of metal loss during lifetime of the project as per standards recommendations.
- Mechanical tests: Tensile tests were made according to ISO 6892 [6], Charpy V-Notch according to ISO 148-1 [7] and Vickers Hardness HV10 according to ISO 6507-1 [8]. 1 set of complete test (tension + Charpy + hardness) was realized per heat number when applicable. In addition a chemical analysis was made per type of product to check the chemical composition.

2. Tests performed on end joining shackles DN120mm R4

a) Visual check and dimensional control

Figure 1 exhibits the general aspect of shackle bodies. It has to be noted that for all bodies, the crown is more eroded than the rest of the body (Figure 2) due to wear with the chain connection. The extrados crown presented high pitting corrosion (Figure 3). The bores of the shackles also exhibit a quite important level of corrosion (Figure 4). The marking area is still readable, ensuring a good traceability.

There is some clear evidence of plastic deformation on three bodies with the closing of jaw gap (Figure 5). One of these shackle bodies has the mark of the head pin all around the bore, the pin itself being heavily marked by the chain print. This phenomenon is probably due to overloading (Figure 6 & 7).

A full dimensional control was performed on all pieces (7 pieces) according to drawing presented in Appendix 1. A comparison was made with the as build report made by Le Béon Manufacturing 10+ years ago. Comparison of forging parts without machining seems to be difficult to establish as dimensions can vary from one point of control to another. These parts are dependent of the operator and measurement points.

A reliable comparison is established with all machining part i.e. pins, holes and nuts. Pins and nuts show an average loss of material of about 0.2mm/year. Holes seems to have been less corroded as they exhibit an average loss of material of 0mm/year maybe due to a less water circulation in these areas.

Products are generally showing a corrosion level below the expected corrosion rate normally considered. Some significant permanent plastic deformation are visible on some shackles.
Figure 1: Shackle body general view

Figure 2: Crown area

Figure 3: Pitting corrosion on extrados of the crown

Figure 4: Corrosion in the bore

Figure 5: Overload evidence (jaw gap closed)

Figure 6: Overload evidence (head marked)

Figure 7: Chain print on pin
b) Break Load Test

According to the dimensional report, the worst dimensional case shackle has been chosen for the proof Load and break Load testing. Loads have been calculated regarding the diameter of corroded grade R4 chain with 0.4mm/year of metal loss during the operation time of the shackle (as defined in class rules). Deformation points were hard stamped on the shackle body in order to evaluate a possible permanent deformation after these two tests. Figure 8 present the location of deformation points on shackle body and Figure 9 show the shackle installed on the test bench.

The shackle body shown a slight increase of 2 mm in jaw gap after proof load. This was the same after break load test (+1mm) and a slight increase in overall length was observed (less than 1mm). Dimensional integrity of the shackle pin was ensured after Proof Load test and it exhibited a bending of about 1mm after break load test. No cracks appeared or developed. The shackle succeed in load tests.

It is however interesting to notice that at break load, the shackle body tends to open (increasing jaw gap). On the other hand, three of the tested shackles show heavy marks of plastic deformation but tend to behave in the opposite matter (jaw gap closing). This could suggest that the shackles have been submitted to even higher loads than the break load during operation.

This theory is however difficult to confirm as the permanent deformation observed is not necessary caused by a unique load, it is more likely due to fatigue cycles. No load monitoring data are available from site to support this hypothesis.

It could however mean that the shackle is getting first “open” and then narrowing when the loads are increasing even more. We would then need to identify a proper damage law model for this analysis, which can be rather complex.
c) Mechanical Tests & Comparison with 2014 production

Mechanical tests have been performed as per drawing detailed below. The same locations have been used to assess similar shackles manufactured earlier this year.

![Diagram of Mechanical Test Samples Location](image)

**Figure 10: Location of samples**

<table>
<thead>
<tr>
<th>Parameter (average value)</th>
<th>Class / project requirements</th>
<th>Shackle (10+ years) Body</th>
<th>pin</th>
<th>Shackle (2014) Body</th>
<th>pin</th>
</tr>
</thead>
<tbody>
<tr>
<td>Toughness @ -20°C (J)</td>
<td>≥50</td>
<td>8.5</td>
<td>20.4</td>
<td>134</td>
<td>152</td>
</tr>
<tr>
<td>Yield strength (N/mm²)</td>
<td>≥700</td>
<td>801</td>
<td>849</td>
<td>760</td>
<td>750</td>
</tr>
<tr>
<td>Tensile strength (N/mm²)</td>
<td>≥880</td>
<td>964</td>
<td>989</td>
<td>928</td>
<td>936</td>
</tr>
<tr>
<td>Elongation (%)</td>
<td>≥12</td>
<td>16</td>
<td>15</td>
<td>20</td>
<td>17</td>
</tr>
<tr>
<td>Reduction in area (%)</td>
<td>≥50</td>
<td>45</td>
<td>56</td>
<td>69</td>
<td>66</td>
</tr>
</tbody>
</table>

Both body and pin have correct tensile properties but poor Charpy values. Despite of this very low toughness, shackles have been used with no major incident for 10+ years and have withstand overloads inducing significant permanent deformation without critical failure. Chemical composition revealed that material is in line with specifications.
3. **Tests performed on triplates for chain DN95mm R4**

   **a) Visual check and dimensional control**

   Only one triplate has been made available for this study, hence the accuracy of the study in trickier. This triplate has been used for 20+ years in West Africa, connecting shackle to shackle. Dimensional checks and comparison with as-built revealed an average corrosion rate for the plate thickness of 0.35mm/year, while bores have been less affected (0.15mm/year average only).

   **b) Break load test**

   No break load tests have been performed on this product as only a piece was available for testing. It has been considered relevant to save the product for mechanical tests in order to avoid potential performances changes generated by a Break Load Test. Part has however been NDT controlled and no significant crack or defect have been reported.

   **c) Mechanical Tests & Comparison with 2014 production**

   Mechanical tests have been extracted area in between both main bores. It is to be noted that the triplates manufactured in 2014 for comparison are not intended to replace the original one, but present similar sections and hence are relevant for comparison.

<table>
<thead>
<tr>
<th>Parameter (average value)</th>
<th>Class requirements</th>
<th>Triplate (20+ years)</th>
<th>Triplate (2014)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Toughness @ -20°C (J)</td>
<td>≥50</td>
<td>55</td>
<td>122</td>
</tr>
<tr>
<td>Yield strength (N/mm²)</td>
<td>≥580</td>
<td>770</td>
<td>724</td>
</tr>
<tr>
<td>Tensile strength (N/mm²)</td>
<td>≥860</td>
<td>983</td>
<td>894</td>
</tr>
<tr>
<td>Elongation (%)</td>
<td>≥12</td>
<td>15</td>
<td>20</td>
</tr>
<tr>
<td>Reduction in area (%)</td>
<td>≥50</td>
<td>47</td>
<td>67</td>
</tr>
</tbody>
</table>

   Parameters of this product are in line with class regulations requirements (except for reduction in area). However looking back at the original certificates (20+ years ago), results described are quite different. Chemical composition revealed that material is in line with specifications.

   Indeed, report from manufacturing period are indicating average Charpy impact values around 95J @ -20°C, hence almost double from what has been observed in forensics.
4. Tests performed on open socket for cable Ø110mm

   a) Visual check and dimensional control

Again, only one socket has been collected for this forensics assessment. Connecting the wire rope with plate. The open socket was originally supplied 10+ years ago with Epoxy paint 400µm thickness as per offshore standard, protected with aluminum type anode. If no anode is present (probably remove during decommissioning activities offshore), voiding the possibility to assess the efficiency of this sacrificial component, it is to be noted that the socket body is in an overall good condition. At locations where scratches have affected the painting shell, some rust has developed but not to a measurable point in term of dimensions changes. For this product, the corrosion rate is estimated at 0mm/year.

The pin being stainless type made, corrosion rate estimation is not relevant.

   b) Break load test

No break load tests have been performed on this product as only once piece was available for testing and no cable was installed.

   c) Mechanical Tests & Comparison with 2013 production

Mechanical tests have been extracted from around the eye location, two different locations in the arms and one location in the cone of the socket. Same approach for the 2013 manufactured socket. Again, it is to be noted that the new-build socket is not intended to replace the original one, but cable size to accommodate is the same and geometry very similar.

<table>
<thead>
<tr>
<th>Parameter (average value)</th>
<th>Class requirements</th>
<th>Open Socket (15+ years)</th>
<th>Open Socket (2013)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Toughness @ -20°C (J)</td>
<td>≥50</td>
<td>35.4</td>
<td>140</td>
</tr>
<tr>
<td>Yield strength (N/mm²)</td>
<td>≥490</td>
<td>725</td>
<td>717</td>
</tr>
<tr>
<td>Tensile strength (N/mm²)</td>
<td>≥770</td>
<td>882</td>
<td>872</td>
</tr>
<tr>
<td>Elongation (%)</td>
<td>≥15</td>
<td>19.5</td>
<td>21</td>
</tr>
<tr>
<td>Reduction in area (%)</td>
<td>≥50</td>
<td>65</td>
<td>69</td>
</tr>
</tbody>
</table>

Socket body has correct tensile properties but poor Charpy values. Stainless steel pin is compliant with class requirements. Chemical composition revealed that materials are in line with specifications. Despite of this low toughness, sockets have been used with no major incident for 10+ years without failure.

5. Summary of the forensics results observed

These tests, even if partially incomplete due to the low quantity of products available revealed some key elements:

- Toughness observed in the various products is not necessary matching the required values of class specifications.
- Some products have been submitted to heavy load generating plastic deformation, without failure despite these low toughness.
- Tests results performed during manufacturing stage 10 or 20 years ago were found conform to specifications.
III. How could it happen?

Out of the data extracted from the forensics programs detailed above, some results are clearly in deviation with some of the requirements of the current rules. (Especially in term of toughness). The connectors tested were however manufactured and tested in full compliance with rules applicable at that time, which means these results are not only LE BEON MANUFACTURING connectors results, but indeed common to the industry of that time. As a consequence, it appears that there is a rather sizeable portion of existing and aging mooring systems potentially equipped with non-compliant connectors.

Industry actors are actually aware of this fact since few years, which was the trigger for developing the Mooring Components Assessment JIP in 2008. Here is an extract from the initial scope of work proposal, written by Bureau VERITAS & Total at that time [9]:

“Recent field failures of mooring components have raised concerns over the current design criteria and material property requirements (e.g., Charpy toughness) as well as their implications on the structural integrity of already installed components like shackles, H-links, tri-plates, cable sockets, etc. Subsequent testing of spare components from separate installations by various organizations has shown that Charpy toughness can vary from values well below to above the required toughness specification (e.g., 50J at -20°C), depending upon sampling location etc. A recent review of the existing data available to date suggests that the problem appears to be more wide-spread than originally thought. Since mooring line components can be subjected to extreme loading conditions such as those induced by hurricanes, e.g., in Gulf of Mexico and typhoons in Asia, their structural integrity must be assured by demonstrating adequate fracture toughness to prevent pre-mature brittle fracture and sufficient fatigue resistance to typical operating conditions.”

1. Relevancy of the tests performed on the connectors


This was actually few months after some of the most serious connectors failure to date in the industry. Even if issued almost immediately the issues, this paper is detailing one of the key reasons explaining how this has happen:

“Historically, below-specification CVN energy components have been observed despite the manufacturer certifications and other QA (e.g., surveillance) indicating sufficient CVN values. The difference results from taking test coupons directly from the components themselves (lower CVN) and the representative material during the manufacturing process (higher CVN). As a result, the manufacturer certifications reflect material that underwent a different process (i.e., heat treatment) than the delivered component. “[10]

Indeed, before 2008, a common practice for connectors manufacturing was the use of external tests coupons. Main reason was cost driven: testing from these “external” coupons saved a sacrificial item to be produced, and hence was not impacting customer unit pricing. As mentioned above, this practice was fully accepted by classes and other parties (including customer inspectors for instance).
Looking more in details at Certification Notes – No.2.6 from DNV issued in August 1995 [12], the chapter regarding mechanical tests is rather brief but explicit:

“For test sampling, forgings of the same nominal thickness originating from the same heat treatment charge and the same heat of steel are to be combined into one test unit. Each sample forging shall either be an individual product forging, or it shall be a representative separate forging made from the same heat of steel and shall receive substantially the same reduction and type of hot working and shall be of the same nominal thickness as the production forgings. The separate test forging shall be heat treated together with the production forgings. From each sample, one tensile and three impact test pieces are to be taken per Figure 9-1 and tested.” [12]

Today, it seems obvious that heat treating a test block (even if same thickness) instead of the real test type is not relevant, and cannot provide reliable data. Indeed, this block is in any case more receptive to heat treat than the real product due to its geometry, size and position in the furnace.

The current applicable specification for Mooring Chain Cables and Accessories from DNV is the DNV-OS-E302 from October 2013 [13]. This successor form the Certification Notes No.2.6 has a stricter focus on Mechanical testing, as detailed below:

“At least one accessory out of every test unit, see [3.5.2], shall be tensile and impact tested in the condition of supply. Except as provided in [3.5.3], test pieces shall be taken from proof load tested or breaking load tested full size accessories. For each test unit, one tensile and three Charpy-V-notch test pieces shall be taken. 3.5.2 A test unit shall consist of up to 25 accessories of the same type, grade and size, made from the same heat of steel, and heat treated in the same furnace charge. 3.5.3 Where the size of a test unit is less than five produced accessories, alternative testing may be agreed provided that:
— the alternative testing is described in a written procedure, and
— the separately forged or cast coupon have a cross-section and, for forged coupon, a reduction ratio similar to that of the accessories represented, and — it is verified by procedure test that coupon properties are representative of accessory properties.” [13]

The possibility to use separated coupons still exists, however the conditions of application are much stricter and the representativeness this coupon towards the real product has to be proven. This is a move in the right direction to ensure a higher level of safety of the product.

In the same trend, looking at the Guide for Certification of Offshore Mooring Chain from ABS dated 1999 [14], it is straightforward to notice that no mechanical tests plans are existing for pins. A convenient way to proceed for a manufacturer at that time would be to produce slightly longer pins that required by the final products, and to extract the mechanical tests from this extra material. Once again, the representativeness from this test is questionable as the surface of contact for the heat treatment is actually more important than on the worst case of the real product. This has been corrected 10 years after in the December 2009 of the Guide for Certification of Offshore Mooring Chain [15], with the following chapter:

“Mechanical tests of pins are to be taken as per Section 2, Figure 1 from the mid length of a sacrificial pin of the same diameter as the final pin. For oval pins, the diameter taken is to represent the smaller dimension. Mechanical tests may be taken from an extended pin of the same diameter as the final pin that incorporates a test prolongation and a heat treatment buffer prolongation, where equivalence with mid length test values have been established. The length of the buffer is to be at least equal to one pin diameter dimension which is removed after the heat treatment cycle is finished. The test coupon can then be removed from the pin. The buffer and test are to come from the same end of the pin as per Section 5, Figure 1. Also refer to 2/3.13 for heat treatment of rolled bars for pins and 2/5.5 for heat treatment of forged pins.” [15]
2. **Gap in the specifications**

A good example at the connector level for a gap in the certification requirements can be found in the Certification Notes No.2.5 from DNV issued in May 1995 [16]. These notes, -the ancestor of the current DNV-OS-E-304 [17] - titled Certification of Offshore Mooring Steel Wire Ropes gives the rules for the wire ropes and the corresponding terminations (mainly sockets).

Regarding the recommendations for sockets, two manufacturing classes are proposed: steel plates made or castings. Innovation and evolution of the market to forged sockets has been considered only few years after. In the meantime, the appreciation of how to qualify forged sockets and approved them was mainly let at class inspector appreciation. Nowadays in the current DNV rules, for forged sockets, a reference is made to the DNV-OS-E-302 (Mooring Chain Cables and Accessories) [13] so that the circle is complete.

3. **Summary of section**

The relevancy and accuracy of the process for sampling mechanical tests from forged connectors has been relatively poor since recently (probably less than a decade ago), mainly due to the questionable representativeness of the “external coupon” widely used by all manufacturers. As a consequence, products which should have been rejected because of non-compliance in term of mechanical performances (Charpy impact especially) were certified and installed. The batch of tests performed at that time (proof load and break load) were of no support to detect this potential below-specification data as the strengths were generally higher than required.

However, this only explains how some none compliant connectors of the industry of that time have been installed under water. Why none compliant products have been manufactured for years is related to the manufacturing process itself and will be discussed in next section.
IV. Results Analysis / Key factors in connectors manufacturing

The following parameters play a key role in the process of manufacturing adequate connectors:

- Raw material quality: to manufacture good final products, you should start with quality raw material. Quality in term of cleanliness, performances, homogeneity and reproducibility.
- Heat treatment accuracy: this treatment involves changes in the microstructure of the material and is critical to ensure that product gets the required mechanical performances.

1. Raw material quality impact

Raw material is undoubtedly the most critical parameter to consider for mooring connector quality. For mooring applications, manufacturers have been using – and are still using - standard steel as per the EN 10083-3 [18] or equivalent, delivered by approved millers as recommended from the class specifications. Starting from a 34CrNiMo6, F22 or 42CD4 type does not change much the picture: a standard raw material, complying with above mentioned standard will generate significant variations in the mechanical properties (up to 100% fluctuation). For this reason, it is questionable if such a “basic” steel can be suitable for critical applications such as mooring connectors. Based on our experience, this type of material can be responsible of significant decrease of the fatigue lifetime and increase of formation and propagation of cracks.

Graph below shows the typical trend of the evolution of Charpy Toughness observed in sacrificial products (i.e. no external coupons) in manufacturer’s real production, for different type of mooring connectors (shackles, H-links, sockets...). Left cloud of results are coming from products manufactured from standard raw material (compliant with Class specification), rights impacts are coming from products submitted to the same forging and heat-treatment process, but based on a customized raw material (i.e. stricter parameters).

The results observed above have been based on hundreds of tests performed by Le Beon Manufacturing on sacrificial products from 2007 up to now and hence can be considered as relevant [19]. The standard deviation in term of Charpy toughness have been reduced by 55% for grade R3 & R3S and by 69% for grade R4. This confirm and explain as well the spread results observed on the various forensics programs performed, from products manufactured well before 2007.
Currently, looking at the IACS W22 [4] and its variants from classes, we can see the beginning of the material recommendation being implemented.

“For acceptance tests, the chemical composition of ladle samples of each heat is to be determined by the steel maker and is to comply with the approved specification.” ABS Guide for the certification of offshore mooring chain. [15]

“The steels shall be killed and fine grain treated. The austenite grain size shall be 5 or finer in accordance with ASTM E112. The fine grain size requirement shall be deemed to be fulfilled if the steels contain Al, Nb, V or Ti, either singly or in any combination, as follows: When Al is used singly, the minimum total content shall be 0.020% or, alternatively, the Al to N ratio shall be minimum 2:1. When Al and Nb are used in combination, the minimum total Al content shall be 0.015% and the minimum Nb content shall be 0.010% When Al and V are used in combination, the minimum total Al content shall be 0.015% and the minimum V content shall be 0.030%.” DNV OS-E-302, Offshore Mooring Chain [13]

Looking more in details in specs from Majors or Contractors like TOTAL for instance (GS-EP-STR-203 [20]), it seems that this gap can be corrected by adding requirements on the limits allowable for residual elements (S, P). These elements are also critical to consider and quantify as they are likely to generate embrittlement at grain boundary.

The cleanliness required for the steel is also not documented to date. (Inclusion properties for instance).

2. Heat treatment accuracy impact

The heat treatment process, following the forging, is composed of two to three stages. The concept of the heat treatment is to modify the internal grain structure of the steel in order to meet the performances required in term of strength, but as well in term of toughness by the material grades.

<table>
<thead>
<tr>
<th>Steel grade</th>
<th>Yield Stress (Re) N/mm²</th>
<th>Tensile strength (Rm) N/mm²</th>
<th>Elongation (A5) %</th>
<th>Reduction of Area (Z) %</th>
<th>Charpy V-notch @ -20°C J</th>
</tr>
</thead>
<tbody>
<tr>
<td>R3</td>
<td>410</td>
<td>690</td>
<td>17</td>
<td>50</td>
<td>40</td>
</tr>
<tr>
<td>R3S</td>
<td>490</td>
<td>770</td>
<td>15</td>
<td>50</td>
<td>45</td>
</tr>
<tr>
<td>R4</td>
<td>580</td>
<td>860</td>
<td>12</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>R4S</td>
<td>700</td>
<td>960</td>
<td>12</td>
<td>50</td>
<td>56</td>
</tr>
<tr>
<td>R5</td>
<td>760</td>
<td>1000</td>
<td>12</td>
<td>50</td>
<td>58</td>
</tr>
</tbody>
</table>

Typical Material Properties per Grade

Some manufacturers will use different raw material to obtain the different grades, while some others will use the same material for a range of grade (R3, R3S & R4 for instance) and adjust the heat treatment parameters in order to match the grades performances.

By essence, this step is probably the second most critical parameter to obtain a product compliant with the needs of the mooring industry.
The chart below describes the main phases, their uses and the inherent risks in case the phase of the process in not performed correctly (incomplete timing, un-appropriated temperature...).

<table>
<thead>
<tr>
<th>Steps</th>
<th>Use</th>
<th>Material Structure</th>
<th>Potential Risks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normalizing (pending manufacturers)</td>
<td>Getting a finer structure</td>
<td>Mainly Bainite</td>
<td>Lower Charpy values at the end of the process</td>
</tr>
<tr>
<td></td>
<td>Stress release from forging</td>
<td></td>
<td>Incomplete stress release</td>
</tr>
<tr>
<td>Quenching</td>
<td>Hardening</td>
<td>Martensite</td>
<td>Structural transformation incomplete, low mechanical performances</td>
</tr>
<tr>
<td>Tempering</td>
<td>Toughness &amp; ductility increase</td>
<td>Tempered Martensite</td>
<td>Migration of residual elements at grain boundary, potential embrittlement</td>
</tr>
</tbody>
</table>

To illustrate the sensibility of the material to the temperatures during heat treatment, a test has been performed on 34CrNiMo6 raw material, square bar of 50mm side. (Same heat batch, same location, laboratory furnaces accuracy ± 2.5°C). For this study, only the sensibility of the material to the tempering temperature parameter is considered.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Batch 1</th>
<th>Batch 2</th>
<th>Batch 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quenching Temperature (°C)</td>
<td>840</td>
<td>840</td>
<td>840</td>
</tr>
<tr>
<td>Tempering Temperature (°C)</td>
<td><strong>600</strong></td>
<td><strong>630</strong></td>
<td><strong>660</strong></td>
</tr>
<tr>
<td>Toughness @ -20°C (J)</td>
<td>127</td>
<td>137</td>
<td>151</td>
</tr>
<tr>
<td>Yield strength (N/mm²)</td>
<td>862</td>
<td>833</td>
<td>778</td>
</tr>
<tr>
<td>Tensile strength (N/mm²)</td>
<td>1005</td>
<td>967</td>
<td>902</td>
</tr>
<tr>
<td>Elongation (%)</td>
<td>17,9</td>
<td>19,4</td>
<td>22,5</td>
</tr>
<tr>
<td>Reduction in area (%)</td>
<td>66,6</td>
<td>66,1</td>
<td>68,4</td>
</tr>
<tr>
<td>Corresponding theoretical grade</td>
<td><strong>R5</strong></td>
<td><strong>R4S</strong></td>
<td><strong>R4</strong></td>
</tr>
</tbody>
</table>

Of course, the sections considered for this study are not representative of real size mooring connectors, however the results are interesting: only by adjusting the temperature by 30°C during tempering stage, the material shift from R5 compliant to R4S only, an additional 30° and material is only R4 compliant.

From this small scale and very sensitive approach, it is possible to generalize the behavior of real size connectors during heat treatment phases, especially at core of the product.

According to API Spec 6A / ISO 10423 Annex M [21], uniformity criteria of the temperature inside the furnaces is defined as such: “The temperature at any point in the working zone shall not vary by more than ±14 °C (25 °F) from the furnace set-point temperature after the furnace working zone has been brought up to temperature. Furnaces which are used for tempering, ageing and/or stress-relieving shall not vary by more than ± 8 °C (15 °F) from the furnace set-point temperature after the furnace working zone has been brought up to temperature.” [21]
Obviously in the past decades, the specifications were not so strict in term of temperature control. The ranges mentioned above are actually already quite large and will generate some fluctuations in term of performances should a connector be placed at different locations in the furnace.

In the industry practices, for cost optimization, the working zones of the furnaces (areas homologated and in which the products to be treated shall be installed) are used as much as possible in order to reduce the number of batch numbers. Indeed, current specs coming from IACS [4] require:

- For Break load: “At least one accessory out of every test unit shall be breaking load tested in the condition of supply and shall withstand without fracture the breaking load prescribed in Table 2-1 for the chain grade and size for which they are intended. It shall be considered acceptable if the samples show no sign of fracture after application of the specified minimum load for 30 seconds. A test unit shall consist of up to 25 accessories of the same type, grade and size, made from the same heat of steel, and heat treated in the same furnace charge” [13]
- For Mechanical tests: “At least one accessory out of every test unit, see [3.5.2], shall be tensile and impact tested in the condition of supply. Except as provided in [3.5.3], test pieces shall be taken from proof load tested or breaking load tested full size accessories. For each test unit, one tensile and three Charpy-V-notch test pieces shall be taken. A test unit shall consist of up to 25 accessories of the same type, grade and size, made from the same heat of steel, and heat treated in the same furnace charge. [13]

With ABS current regulations [15], the rule is even stricter as a break load test and a sacrificial accessory should be tested out of each test unit. Obviously, the more pieces in the furnace charge—or the bigger the furnace—the less sacrificials are required. This can have a positive impact in term of connectors pricing. This practice is however not in favor of product quality.

“Finished forgings are to be properly heat treated in compliance with specifications submitted and approved.

- Forgings in furnaces are to be positioned so that the heat transfer between furnace and forgings is not influenced by other forgings.
- Forgings are not to be stacked on top of each other in the furnaces.
- Positions of forgings in furnaces are to be recorded.
- During quenching, forgings are to be positioned so that the heat transfer between quenching medium and the forging is not influenced by other forgings.
- During accelerated cooling after tempering, forgings are to be positioned so that the heat transfer between quenching medium and the forging is not influenced by other forgings.” [15]

Indeed, even if stacking is nowadays prohibited (as mentioned above in ABS specification), the temptation to apply minimum gap in between the parts exist in order to optimize the charges. The concept “is not influenced but the others” being quite relative.

Using bigger furnaces is not quality improvement driven neither, in the way that the conditions faced in between the center and the side of the furnaces will be even more different than in a small batch (interferences from the side products during heating and quenching phases, impacting the heating and cooling ratio). As a result, product from the center might not have received enough heat (or a fast enough quenching process), and this will not necessary be picked up by the tests (as only a random check of 4% only (1 out of 25 accessories in the worst case) will be performed).

Considering the rules applicable in the past—and still today-, it is also possible to get significant fluctuations inside a product itself, i.e. from a location to another. This is a potential consequence from a poor material control (i.e. with significant properties changes, impurities) and a perfectible heat treatment.
Study presented below is based on an open socket, with raw material on specifications and upgraded heat treatment (stricter than class). For this product, only two socket at the time were composing the furnace and quenching load, reducing to a minimum the potential interferences in between the elements for heat transfer quality.

Out of 6 tensile tests
**Out of 18 single Charpy tests

This study needs to be compared with results from previous practices (standard raw material and less accurate heat treatment) to understand the progresses performed in 10+ years. However, it appears that the deviations of material performances from one part to another are minor and hence the product is very homogeneous.
Similar study program have been performed from socket mentioned in section II forensics program (standard raw material and bigger furnaces for heat treatment process) with more focus on Charpy impacts, results as shown below:

<table>
<thead>
<tr>
<th></th>
<th>Yield Strength (N/mm²)</th>
<th>Tensile Strength (N/mm²)</th>
<th>Elongation (%)</th>
<th>Reduction in Area (%)</th>
<th>Charpy @ -20°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average</td>
<td>725</td>
<td>882</td>
<td>19,5</td>
<td>65</td>
<td>35,4</td>
</tr>
<tr>
<td>Std Deviation</td>
<td>14*</td>
<td>10,6*</td>
<td>2,9</td>
<td>3</td>
<td>12,3**</td>
</tr>
<tr>
<td>Relative deviation</td>
<td>1,9*</td>
<td>1,1*</td>
<td>15</td>
<td>4,5</td>
<td>41,8**</td>
</tr>
</tbody>
</table>

*Out of 2 tensile tests  
**Out of 8 single Charpy tests

There is an important fluctuation of the toughness inside the product itself from an area to another. This is mitigating today at Le Beon Manufacturing by freezing the raw material performances (raw material on specs), working with an accurate heat treatment process and performing pre-machining operations before the heat treatment in order to reduce the mass and thicknesses to be heat-treated.
V. Lessons Learned & Future Challenges

1. Lessons learned

From the industry of a decade ago (and more), two main parameters can explain the fluctuations observed in the results during the forensics on forged products:

- The raw material absence of consistency
- Lack of control & accuracy during the heat treatment

Poor temperature control, lack of care in term of furnaces loading, transfer times & baths agitations have been root causes for poor or incomplete heat treatment process in the past.

- Today an increasing attention is given to heat treatment, in term of controls, in term of monitoring of the load and calibration of the furnaces. It is however still surprising to observe that smaller heat batches (from smaller and hence potentially more accurate furnaces) are still in deviation with class regulations and require case by case approval. On the other hand, bigger furnaces are relatively low controlled with a frequency reduced up to 1 piece out of 25 despite a poorer accuracy and hence more fluctuations in term of material performances. To summarize, it basically implies that a robust and low deviation process is currently more monitored and tested than a bigger and more fluctuating process.

Alternative heat treatment processes are being studied and implementing by connector manufacturers to improve the quality of the products (continuous heat treatment, individual heat treatment). These processes will require to reconsider the current regulations in term of batch sampling control and induce a change of mentality from the certification classes.

- A low level of recommendations is currently existing regarding the raw material quality from class societies. This is rather surprising considering the impact of the raw material quality on a production homogeneity and inside a single product itself. Various Joint Industry Projects exist to assess or improve mooring elements quality (Mooring Components JIP, SCORCH JIP, HPSM JIP, Mooring Systems Future JIP), but none of them is focussing on the raw material. Millers are so far not part of any of these working groups, which demonstrate that the focus on raw material is still too limited.

Raw material and heat treatment are two assemblies working as a couple, focusing only on one will not be enough to ensure quality products. On the other end, having a well-controlled raw material (typically on specs) AND an accurate heat treatment (through smaller furnaces or other concepts) will ensure reliable and reproducible results.

With today’s perspective and conclusions from JIP MCA being available, the forged connectors produced by industry over the past years and considered as not compliant have however been performing well for the lifetime of the project in their vast majority. Statistics extracted from data field by Mr. KT Ma [1] suggest that should a mooring line fail for unappropriated design of manufacturing none compliance, this is likely to happen during installation or very early in the lifetime of the project (also describe as “infant mortality of mooring system”).

From the point of view of a mooring connector with below-specification material fracture toughness, it indeed seems applicable: these products can be sensitive to cracks propagation, generating failure. The risk of getting these cracks propagating is mainly concentrated during installation phases, where shocks and poorly controlled tensions can happen. Once in normal operation and running in the designed working conditions, the risk for cracks to develop is very minor. This explains that very few mooring failures –two reported up to date- are actually directly related to low toughness.
2. Future Challenges

As the offshore industry is progressing to always deeper and harsher environments (Arctic conditions and ultra-deepwater), the need for higher capacity mooring systems is growing. One of the solution to address this challenge is to focus on higher material grades (R5 and higher typically).

There is nothing new in observing a time gap in between innovation and corresponding regulations settings the standard for this innovation, however the fact –as an example- that class societies do not have the same criteria in term of R5 grade homologation should contribute to a conservative approach. Higher grade materials are of course more sensitive and difficult to handle, and hence even stricter rules should exist to mitigate the potential risks. With the current level of specifications, the risk of failure cannot be considered as negligible. The material behaviour at very low temperature might fluctuate a lot (from typical ductile to brittle conditions), especially for higher grades.

Another trend which is emerging is the need for separating the specifications of chain from the ones of connectors. If historically both have been addressed under the same regulation, they belong to two different field of expertise. For instance, is it relevant to limit the carbon equivalent (Ceq) of a mooring connector which per rules cannot be welded? Does it make sense to define the required CTOD value (Crack tip opening displacement) with values obtained from the chain, even if materials are quite different? API 2F committee has already confirmed the approach of splitting both specifications in the coming updated version of the specification.

Finally, fatigue is a raising concern for mooring system (so far mainly considered for chain applications). In the past years, fatigue was almost never blocking for connectors design, with theoretical lifetimes estimated at hundreds of years or more. Recently however, fatigue spectra have become more demanding and are starting to be limiting. Real size fatigue tests are common for chain, this should also be generalized to connectors in order to get better understanding of mechanics involved.
References


[4] International Association of Classification Societies, W22 Offshore Mooring Chain, June 2010


[12] Det Norske Veritas Classification AS, Certifications Notes No.2.6, Certification of Offshore Mooring Chain, August 1995


[16] Det Norske Veritas Classification AS, Certifications Notes No.2.5, Certification of Offshore Mooring Steel Wire Ropes, May 1995


[18] DIN EN 10083-3, Steels for quenching and tempering, Technical conditions for alloy steels, 2012

