SUSCEPTIBILITY TO BRITTLE FRACTURE OF FLANGES IN ASTM A105.

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ABSTRACT

The incentive for the present study was a brittle fracture that occurred in a 101 mm thick 24" welding neck flange of Class 600 according to ANSI B16.5. This component, with a coarse grain microstructure, was installed in a high-density polyethylene (HDPE) loop reactor and failed presumably at a temperature of -16 °C.

In this project, a large number of ASTM A105 carbon steel flanges has been investigated with the main purpose of evaluating the material's fracture toughness and defect tolerance. Investigations revealed large variations in microstructure, grain size and hardness, depending on the manufacturing route and heat treatment. Even multiple small hydrogen cracks were found in two of the investigated 24" flanges. Toughness has been evaluated by notch impact and CTOD fracture toughness tests at different low temperatures. A correlation was made between microstructure, grain size and fracture toughness. A fitness-for-purpose analysis, based on CTOD fracture toughness, allowed to assess the risk for brittle fracture in large (24" / Class 600) carbon steel flanges complying with ASTM A105.

1. INTRODUCTION

Codes, ASME VIII div.1 and ASME B31.3 allow carbon steel conforming to ASTM A105 [1] for applications down to a minimum temperature of -29 °C (-20 °F).

In January 1998, Borealis Beringen (Belgium) experienced brittle fracture in a raised face 101 mm thick 24" welding neck flange of Class 600 operating in the loop of a reactor of an HDPE-unit since 1990. Due to a power dip in the plant, the product in the reactor boiled at atmospheric pressure, resulting in cooling of the reactor and the loop to about -16 °C. The line was partly plugged with solid product at the location of the failed flange, which resulted in an uneven cooling of this flange. It was assumed that, close to the boiling product, the temperature of the flange was about −16 °C but about +60 °C at the location of the plug, see Figure 1. The flange cracked at the transition between the conical and cylindrical part of the welding neck, see Figure 2, at a location coinciding with the cold area.

Previous investigations at the Belgian Welding Institute (BWI) revealed that the flange had a coarse grained (ASTM grain size number 5 to 6) ferrite-pearlite microstructure, see Figure 3. The 27 J Charpy-V impact transition temperature was about +10 °C. An additional heat treatment at BWI (normalising at 900 °C for one hour) resulted in grain refinement to ASTM grain size number 9, see Figure 4, and in a shift of impact transition temperature to below -30 °C.

As a result of this, a research project has been initiated with the following main objectives:
to get a better understanding of the relation between microstructure, grain size, hardness and fracture toughness properties of flanges in carbon steel complying with ASTM A105 - to formulate recommendations and requirements for flanges actually in use in different plants as well as for new installations.

2. INVESTIGATED MATERIAL

Within the scope of a fitness-for-purpose analysis, a series of flanges with different sizes and of various rating classes has been fully characterised.

To achieve this, the fractured 24" / Class 600 flange from Borealis (symbolised hereafter by FLA) has been retained for further investigation as well as two other flanges of same size and rating class (symbolised by FLB and FLD), which were removed from the HDPE reactor. Moreover, twenty new flanges with different sizes and rating classes, manufactured in carbon steel conforming to ASTM A105 have been ordered at one supplier (stockist). Flanges were obtained from three different manufacturers together with EN10204:3.1B certificates.

An overview of all investigated welding neck flanges and most important topics is given in Table 1. According to the relevant certificates, all flanges received a normalising heat treatment after forging, which, according to ASTM A105, is only mandatory for flanges above Class 300.

3. TEST PROGRAMME AND RESULTS

The investigation of in total twenty-three flanges included chemical analyses, metallographic examinations, hardness measurements and mechanical testing consisting of notch impact, tensile and CTOD fracture toughness tests. The main outcome of this is given in the following paragraphs.

3.1 Metallography

The results of surface replica examinations and hardness measurements (made by means of a portable field apparatus, type Microdur) are included in Table 1. From this, one can observe that the original 24" flanges from the HDPE reactor had not been normalised correctly resulting in a coarse grained microstructure.

Similarly, the twenty investigated new flanges show a large variation in grain size. Also in this case it is clear that some of the flanges were not or incorrectly normalised, although officially mentioned on the accompanying certificates.

Besides, the metallographic examinations on radial cross sections revealed that microstructure, grain size and hardness can vary substantially within one and the same flange and therefore raise questions about its homogeneity. Indeed, the difference between minimum and maximum individual ASTM grain size numbers measured per flange varied from 1,3 to 2,3. The mean values for each flange are given in Table 1 and are considered within this study as the most representative grain size for each flange separately.
However, a correct normalising heat treatment at 910 °C for 30 minutes performed by BWI on the unfractured flange FLD yielded a fine grain and a fairly homogeneous microstructure (ASTM grain size number 9,8) over the whole thickness with little variation in grain size (1,3) and hardness. This again is an indication that the heat treatment during manufacturing in many cases has not been performed properly.

Also heat treatment trials realised on pieces extracted from the unfractured flange FLB demonstrate that the test material is not sensitive for grain growth as longer exposure times and higher temperatures do not really affect the grain size.

### 3.2 Cracks in 24" / Class 600 flange FLB and FLV

Metallographic and ultrasonic examinations have revealed multiple small cracks (up to 2 mm long) in two of the investigated flanges, see Figure 5. The nature and morphology of these cracks indicate that these were typical hydrogen cracks or so called flakes. SEM investigation revealed a brittle cleavage type of fracture.

Such internal fissures are attributed to stresses produced by localised transformation and decreased solubility of hydrogen during cooling after hot working [2]. Hydrogen in excess of 5 ppm plays an important role in this phenomenon and can be prevented by degassing treatments. Vacuum degassing treatments are the most efficient and consistent way of reducing hydrogen levels to less than 3 ppm, but there are high capital running and maintenance costs. Soaking treatments are costly and time consuming, especially for large section sizes. Also slow cooling after forging can be beneficial: this slow cooling operation presumably permits the hydrogen to diffuse out of the steel and thereby minimises the susceptibility to flaking.

### 3.3 Mechanical properties

#### 3.3.1 Notch impact toughness

Notch impact data obtained on longitudinal standard test samples showed that the impact toughness of flanges with a coarse grained microstructure (including the fractured flange FLA) is quite low, see Figure 6. The transition temperature corresponding of such flanges with a mean impact toughness of 27 J is about +20 °C. At the minimum operating temperature of -29 °C allowed by ASME B31.3, these flanges possess an impact toughness of less than 10 J.

As expected, flange FLD normalised at BWI exhibits a much better impact toughness transition behaviour with mean values of at least 40 J down to -29 °C. Impact toughness values of nearly 27 J have been obtained even at -46 °C.

The impact data thus demonstrate that material complying with ASTM A105 can exhibit an extremely different impact toughness transition. Indeed mean notch impact toughness for instance at -46 °C and at +20 °C can vary respectively between 3 J (flange FLT) and 68 J (flange FLK) and between 30 J (flange FLR) and 185 J (flange FLJ).
Apparently, the impact toughness is mainly governed by the grain size. A fine-grained test material (ASTM grain size number of 9 or higher) undoubtedly leads to a better impact toughness behaviour than a coarse-grained test material (ASTM grain size number of 7 or lower).

To illustrate the relation between grain size and impact toughness, a summary of mean grain sizes detected by metallography and 27 J transition temperatures for all flanges is given in Figure 7. This figure shows that in general a fine- and a coarse-grained material respectively possess a transition temperature below −40 °C (good behaviour) and above 0 °C (bad behaviour). Surprisingly one 12" / Class 600 flange (FLL) with a coarse grain microstructure has yielded an acceptable notch impact behaviour with a 27 J transition temperature of −35 °C.

3.3.2 CTOD fracture toughness

CTOD fracture toughness tests have been done on 24 mm thick square section three point bend specimens removed in longitudinal direction from the inner side of four flanges with different grain sizes. All specimens were fatigue notched from the outside of the flange while CTOD fracture toughness testing was realised according to BS4778:Part1:1991 in the temperature range between -29 °C and +20 °C.

The test results are summarised in Table 2. The untreated, coarse-grained flanges FLA and FLB possess a moderate fracture toughness while flange FLD, normalised at BWI, exhibits an excellent resistance against brittle fracture initiation. Flange FLK with the intermediate grain size (although still with a mean ASTM grain size number of 9,1) amazingly yields by far the best CTOD fracture toughness at all temperatures. The reason for this is that nearly all samples removed from flanges FLD and FLK exhibited a maximum force plateau behaviour so that the results have been governed by other material properties than the resistance against fracture initiation (strain hardening, resistance against ductile tearing, ...).

4. DISCUSSION

From the metallographic examination, it is concluded that about 40% of the investigated flanges has not been heat treated properly after forging despite the accompanying certification that all flanges had been normalised. This is evidenced by the coarse grained microstructure and presence of Widmanstatten ferrite.

This is fully in line with the findings of Bartlett, Frost and Bowen [3] who have studied the fracture toughness and defect assessment of low temperature carbon steel flanges complying with ASTM A350. The study was typically for gas-plant piping systems where fitness-for-purpose needs to be established at a temperature of -64 °C. This is the lowest temperature that can be reached on theoretical grounds if rapid depressurisation of the system occurs following a process trip or fault condition.

They also observed that many large steel flanges possess poor toughness. A rejection rate of up to 40% (16 flanges out of a sample of 44) has been reported on flanges ordered to ASTM A350 LF2 (requiring a minimum impact energy of 20 J at -46 °C in a standard Charpy impact test). Problems are believed to arise because
accompanying test certificates are often based on smaller-scale test bars supplied from the same heat of material. While such test bars may be considered representative of the chemical composition of the entire heat, it is unlikely that they can represent accurately the forging and heat-treatment schedules performed subsequently to produce the final flanges. It should be noted that although certification anomalies are found occasionally, little evidence of in-service toughness problems with such flanges has ever been reported.

Table 2: CTOD fracture toughness of flanges with different grain sizes
(underlined data are minimum “critical” properties)

<table>
<thead>
<tr>
<th>Flange</th>
<th>Test temp. (°C)</th>
<th>CTOD values (mm)</th>
<th>Fracture behaviour [*]</th>
</tr>
</thead>
<tbody>
<tr>
<td>FLA (Fractured)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ASTM 6,7</td>
<td>+20</td>
<td>0,58-0,15-0,60</td>
<td>m / f / m</td>
</tr>
<tr>
<td></td>
<td>0</td>
<td>0,36-0,14-0,12</td>
<td>f / f / f</td>
</tr>
<tr>
<td></td>
<td>-29</td>
<td>0,27-0,09-0,12</td>
<td>f / f / f</td>
</tr>
<tr>
<td>FLB (Untreated)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ASTM 6,2</td>
<td>+20</td>
<td>0,17-0,08-0,11</td>
<td>f / f / f</td>
</tr>
<tr>
<td></td>
<td>0</td>
<td>0,05-0,06-0,10</td>
<td>f / f / f</td>
</tr>
<tr>
<td></td>
<td>-29</td>
<td>0,09-0,08-0,04</td>
<td>f / f / f</td>
</tr>
<tr>
<td>FLD (Normalised at BWI)</td>
<td>+20</td>
<td>0,41-0,44-0,60</td>
<td>m / m / m</td>
</tr>
<tr>
<td>ASTM 9,8</td>
<td>0</td>
<td>0,56-0,61-0,62</td>
<td>m / m / m</td>
</tr>
<tr>
<td></td>
<td>-29</td>
<td>0,62-0,59-0,55</td>
<td>m / f / m</td>
</tr>
<tr>
<td>FLK (Untreated)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ASTM 9,1</td>
<td>+20</td>
<td>0,90-1,51-1,32</td>
<td>e / m / m</td>
</tr>
<tr>
<td></td>
<td>0</td>
<td>1,39-1,36-1,44</td>
<td>m / m / m</td>
</tr>
<tr>
<td></td>
<td>-29</td>
<td>1,52-1,35-1,50</td>
<td>m / m / m</td>
</tr>
</tbody>
</table>

[*] m = maximum force plateau
     f = unstable fracture (case “c” or “u” of BS4778)
     e = end of clip gauge

The regression line of all data points given in Figure 7, each determined by means of eighteen impact tests and about forty to fifty grain size measurements, proves that a material should have at least an ASTM grain size number of 7,3 or 8,1 in order to guarantee a maximum impact transition temperature of respectively -10 °C or -29 °C. If it is accepted that the detected variation in grain size number across an entire flange follows a normal distribution (with a measured standard deviation of 0,4) and if it is required that at least 90% of the material should be adequate, then the mean grain size number of the flange should be 0,5 higher than the grain size number required above.

Because of this detected variation but also because of the deviation between the grain size measured by replica and by metallography at the same location (due to different orientation of both samples) one single measurement should yield a grain size number which is at least 1,3 above the mean level assuring adequate toughness. If the number of replicas can be increased up to four then this average grain size should only be 0,8 above the required mean level for the flange.
This conservative approach permits to deduce that the ASTM grain size number determined on one single replica should be at least equal to 9,1 (7,3+0,5+1,3) or 9,9 (8,1+0,5+1,3) to assure sufficient toughness respectively at -10 °C or -29 °C. If instead it is possible to prepare four replicas evenly distributed over the circumference then the mean ASTM grain size number should be at least 8,6 (7,3+0,5+0,8) or 9,4 (8,1+0,5+0,8) depending on the minimum operating temperature. More replicas are needed to further relax these requirements but this would increase the procedural costs to unpractical levels.

These very stringent criteria are necessary because of the “limited” number of replica examinations within this project. The correlation between the grain size detected by replica and the mean grain size determined on radial cross sections therefore cannot be assessed statistically. Only observed ranges of deviations can be used which should be appropriately interpreted in order not to overestimate the material’s fracture toughness and defect tolerance.

On the other hand, Figure 7 also demonstrates that flanges complying with ASTM A105, have 27 J impact transition temperatures not higher than +20 °C. If severe stresses may develop only at ambient temperatures or higher, then it is clear that these flanges may be used without taking further precautions in the as-delivered condition.

5. FITNESS FOR PURPOSE

If, as stated before and as general criterion, it is accepted that a pressure part can only be exposed to design conditions of stress and strain at temperatures at or beyond its 27 J transition temperature, then only eleven out of the twenty-three flanges may be taken into service working at temperatures down to -29 °C. If all flanges fabricated following the said ASTM standard should be accepted then the minimum design temperature should be about ambient temperature.

Another possible evaluation may be developed from a fitness-for-purpose analysis following BS 7910:1999 [4] “Guide on methods for assessing the acceptability of flaws in metallic structures”, which is based particularly on CTOD fracture toughness. This evaluation permitted to determine at –29 °C maximum tolerable defect sizes for assumed stress conditions.

Indeed in the normal loading conditions of internal pressure and bolt-tightening, a material having the tensile (yield of 290 MPa) and toughness (CTOD of 0,09 mm) properties of those detected for the failed flange can withstand at -29 °C a sharp surface defect at the intersection of the conical part and the pipe section of maximum 1,5 mm deep and 7,5 mm long (or any equivalent non-planar defect). Long surface defects (even over the whole circumference) of maximum 0,7 mm deep can be allowed under the same conditions without risk for brittle fracture.
These conclusions are based on a Level 2A or normal assessment and includes so called partial safety factors on applied stress, defect size and toughness valid for a failure probability of 0.001 (events/year). It is generally advised to take account of safety factors due to the uncertainty in input data necessary for the assessment.

If non-destructive testing is capable of detecting such flaws and if a proper repair procedure can be realised then the risk for brittle fracture initiation in these flanges is presumed to be acceptably small. These acceptance levels may not be viewed as new criteria for quality control or good workmanship levels as applying a fitness-for-purpose analysis based on an Engineering Critical Assessment or ECA should be done only exceptionally. The occurrence of defects even acceptable to BS7910 instead should be regarded as a need for improving the manufacturing quality.

6. CONCLUSIONS

A first important conclusion is that in many cases, data on the certificates do not comply with the obtained test results. Indeed impact data mentioned on certificates are consistently higher compared to those actually measured on the forged flanges. Also the certified heat treatment (normalisation) is either incorrect or has not been performed at all. This results in a large grain size and poor toughness. Moreover, the S-, Cr- and Cu-contents of one flange, although acceptable, do not correspond with the composition mentioned on the certificate. This shows that the particular flange has been produced from another heat than the one indicated on the certificate. Finally, the carbon equivalent of the flanges (ranging from 0.36 to 0.47) is systematically higher than the carbon equivalent indicated on the certificates. The largest difference was measured on the 18" / Class 600 flange FLY (0.45 versus 0.38). This has a repercussion on the weldability of the material (hardening and cold cracking susceptibility).

It is further concluded that the investigated 24" / Class 600 flanges removed from the HDPE reactor have not been correctly heat treated before installation, although this is mandatory following ASTM A105 for all flanges above Class 300.

Many small cracks were detected in two of the investigated 24" / Class 600 flanges, which were typical hydrogen cracks (flakes).

The notch toughness strongly varies from flange to flange and is closely related to the measured grain size. Microstructure and grain size may also vary considerably within the same flange. However, this phenomenon has not caused a lot of scatter on the material's tensile, hardness and toughness properties.

Anyhow, determination of grain sizes based on replica examinations should be done on a minimum of four locations per flange. The required mean ASTM grain size number determined from the present investigation is 8.6 or 9.4 to assure an appropriate toughness respectively down to -10 °C or -29 °C. Otherwise, it is unsafe to apply ASTM A105 flanges at such conditions. The advantage of this technique is that it can be applied on existing and on new flanges.
It is recommended to perform ultrasonic as well as replica examinations on all flanges before putting them into service.

A fitness-for-purpose analysis following BS7910:1999 “Guide on methods for assessing the acceptability of flaws in metallic structures” has shown that under conditions of internal pressure and bolt-tightening a surface defect at the intersection of the conical part and the pipe section of maximum 1,5 mm deep and 7,5 mm long can be tolerated at –29 °C in flanges complying with ASTM A105. Long surface defects of maximum 0,7 mm deep can be allowed under the same conditions. If such flaws can be detected and repaired then the risk for brittle fracture initiation is virtually excluded.

Acknowledgements

This study has been funded by the Belgian “Federaal Ministerie van Tewerkstelling en Arbeid – Administratie van de Arbeidsveiligheid – Directie van Chemische Risico’s”.

The author’s are grateful to the members of the steering group for their valuable discussions and suggestions: Federaal Ministerie van Tewerkstelling en Arbeid, Solvay, Borealis Polymers, Fina Antwerp Olefins, Fina Raffinaderij Antwerpen, Monsanto Europe and Distrigas.
<table>
<thead>
<tr>
<th>Flange</th>
<th>Size / Class</th>
<th>Forging Temperature (Certificate)</th>
<th>Normalising Temperature (Certificate)</th>
<th>Hardness - Microdur</th>
<th>ASTM grain size number (replica)</th>
<th>ASTM grain size number (metallography)</th>
<th>27J Transition Temperature</th>
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</thead>
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<td>FLA</td>
<td>24&quot; - 600Lbs</td>
<td>?</td>
<td>?</td>
<td>172</td>
<td>6,5</td>
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<tr>
<td>FLB</td>
<td>24&quot; - 600Lbs</td>
<td>1230°C</td>
<td>920°C - Still air</td>
<td>136</td>
<td>8,6</td>
<td>7,3</td>
<td>20°C</td>
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<tr>
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<td>12&quot; - 150Lbs</td>
<td>?</td>
<td>900°C - Still air</td>
<td>147</td>
<td>8,6</td>
<td>7,4</td>
<td>-4°C</td>
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<tr>
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<td>?</td>
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<td>84</td>
<td>7,4</td>
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<td>?</td>
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<td>149</td>
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<td>7,4</td>
<td>-10°C</td>
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<td>149</td>
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<td>149</td>
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<td>7,4</td>
<td>-5°C</td>
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<tr>
<td>FLI</td>
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<td>1180°C</td>
<td>910°C - Still air</td>
<td>140</td>
<td>8,7</td>
<td>9,1</td>
<td>-55°C</td>
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<tr>
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<td>910°C - Still air</td>
<td>140</td>
<td>8,7</td>
<td>9,1</td>
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</tr>
<tr>
<td>FLK</td>
<td>12&quot; - 600Lbs</td>
<td>?</td>
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<td>140</td>
<td>8,7</td>
<td>9,1</td>
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<tr>
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<td>910°C - Still air</td>
<td>140</td>
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<td>9,1</td>
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<td>FLY</td>
<td>18&quot; - 600Lbs</td>
<td>1180°C</td>
<td>910°C - Still air</td>
<td>140</td>
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<td>9,1</td>
<td>-55°C</td>
</tr>
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<td>FLP</td>
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<td>910°C - Still air</td>
<td>140</td>
<td>8,7</td>
<td>9,1</td>
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</tr>
<tr>
<td>FLQ</td>
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<td>?</td>
<td>900°C - Still air</td>
<td>140</td>
<td>8,7</td>
<td>9,1</td>
<td>-55°C</td>
</tr>
<tr>
<td>FLR</td>
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<td>1180°C</td>
<td>910°C - Still air</td>
<td>140</td>
<td>8,7</td>
<td>9,1</td>
<td>-55°C</td>
</tr>
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<td>FLS</td>
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<td>1180°C</td>
<td>910°C - Still air</td>
<td>140</td>
<td>8,7</td>
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<td>1180°C</td>
<td>910°C - Still air</td>
<td>140</td>
<td>8,7</td>
<td>9,1</td>
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<td>FLV</td>
<td>24&quot; - 600Lbs</td>
<td>1180°C</td>
<td>910°C - Still air</td>
<td>140</td>
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<td>FLW</td>
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<td>1180°C</td>
<td>910°C - Still air</td>
<td>140</td>
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<td>FLX</td>
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<td>140</td>
<td>8,7</td>
<td>9,1</td>
<td>-55°C</td>
</tr>
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</table>

Flanges FLA, FLB and FLD have been removed from HDPE loop reactor - Flanges FLE to FLX are new flanges

(*) ASTM grain size number after normalising
(Blank page not to include in Proceedings)
Figure 1: Uneven temperature distribution in the 24” / Class 600 flange FLA
Figure 2: Brittle fracture location in the 24” / Class 600 flange FLA
Figure 3: Microstructure of the broken 24” / Class 600 flange FLA (ASTM grain size number from previous investigation: 5 to 6) – same magnification as Figure 4

Figure 4: Microstructure of the broken 24” / Class 600 flange FLA after normalising trial at 900 °C for one hour (ASTM grain size number from previous investigation: 9)
Figure 5: Small hydrogen cracks in the 24” / Class 600 flange FLB
Figure 6: Notch impact temperature transition curves for flanges removed from the HDPE reactor (FLA = fractured flange; FLB = untreated flange with microcracks; FLD = flange normalised at BWI)

Figure 7: 27 J impact transition temperature against mean grain size for all investigated flanges (open symbols = Class 150, closed symbols = Class 600)
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2. Hydrogen in steel castings.
   The Casting Development Centre
   Technical Bulletin No. 50

   Bartlett, R.A.; Frost, S.R. and Bowen, P.