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HIC TESTING OF A516 GRADE 70 STEELS

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ABSTRACT

Testing for hydrogen-induced cracking (HIC) susceptibility of plate steels is now done routinely for process vessels exposed to wet sour service. A review is presented on the effect of various steelmaking practices on HIC testing behavior of the commonly employed SA516 carbon steel. In particular, variables such as sulfur content, casting (ingot versus continuous), and inclusion content are discussed. Commercial production results for the past several years are presented. Correlations amongst parameters are identified. Comment is given on the use of various calculation methods for specifying HIC test performance. The use of average measurements is recommended. Experiences with the testing of thick plates are reviewed.

Keywords: Steel, steelmaking, A516, sulphur, hydrogen induced cracking, HIC testing.

INTRODUCTION

Evaluating the performance of process vessel steels to hydrogen induced cracking (HIC) test methods is now commonly performed. Applications for steels having to meet these requirements usually involve exposure to wet, sour H_2S service or other specialized petrochemical environments. The important steelmaking controls that must be used to produce steels that perform well in a HIC test have been well defined.(1) Meeting HIC test requirements has been one of the most demanding in utilizing clean steel technology. Inclusions present in the steel, e.g., sulfides or oxides, initiate HIC;

subsequent propagation of cracking in the steel is minimized by having a refined, tough microstructure. Initial work on the development of steels with HIC resistance took place on linepipe materials. This expertise has been translated to process vessels, where the most commonly used specification is SA516 Grade 70, which is most often used for ambient to moderate temperature pressure vessels and piping. A schematic of the formation of HIC is shown in Figure 1 and this emphasizes the association of the phenomena with inclusions. Cracking propagates in planes parallel to the surface of the plate. If inclusions are close to one another, the cracking can link-up in a step-wise array that can be quite extensive and of significant concern.

HIC behavior, as noted above, is related to the cleanliness and microstructure of the steel. Production of HIC tested steels, therefore, concentrates on these two areas. Initial work[1] identified the key variables of importance, these include use of extra low sulfur levels with calcium, inclusion shape control. A516 steel should be heat treated either through normalizing or by quenching and tempering to provide the optimum microstructure of the steel. Both of these heat treatments produce a fine ferrite-pearlite structure with good toughness. Furthermore, it has been established that other production concerns, such as the chemistry of the steel (carbon equivalent) and the casting method (whether ingot or continuous cast), do not play a primary role in this phenomena. The importance of some of the key variables in producing steels with good HIC test performance are reviewed in the subsequent paper.

The requirements for producing HIC tested steel differ depending on individual company specifications. Currently, the most widely used and referenced document for evaluating steels to HIC test requirements start with the NACE TM-02-84 specification[2] which details how testing should be performed. The testing solutions that are utilized for this evaluation include both the higher pH solution noted in this specification and a lower pH solution detailed in NACE specification TM-01-77.[3] The requirements that must be met for producing HIC tested steel also vary for different specifications. They include differences in requirements based upon crack length ratio, or other parameters, differences in sampling of very thick plate and differences in performing the calculations for the actual requirement. Recent production experience is used as a basis for evaluating each of these concerns in the following paper.

PRODUCTION OF HIC TESTED STEELS

Production experience over the last four years has allowed identification of the important control variables in the manufacture of HIC tested steels. These include a number of previously defined items, as well as the importance of cleanliness and microstructural refinement. The general steelmaking procedures that were utilized are shown in Figure 2. All steel is melted in the electric arc furnace, where producing clean steels starts with proper scrap selection. After melting and modest refinement in the electric arc furnace, steel is taken to a ladle furnace station. At this location, the primary desulfurization and chemistry control takes place. As HIC test specifications have become more aggressive, the need for extra low sulfur requirements have been identified. Some specifications can be met with 0.002% sulfur and other requirements necessitate 0.001% maximum sulfur levels. Figure 3 shows a distribution of the sulfur levels that have been obtained over the last several years. It is also generally considered important to have low phosphorus levels in HIC tested steels. Production experience in this area is summarized in Figure 4. Maximum phosphorus levels, as low as 0.005% can be achieved when specified.

After the steel has achieved the proper chemistry, it is then taken to the tank degassing station. At this facility, hydrogen is removed from the steel to assist in improving processing in subsequent parts of the mill. Floating out of remaining inclusions and additional calcium treatment is also achieved at this location. Furthermore, at this facility the chemistry can be fine-tuned. This is important to facilitate meeting very strict carbon equivalent requirements. Although carbon equivalent itself is not found to play a direct role in HIC, it has a very important affect on the hardness of the heat-affected zones in weldments. Hard heat-affected zones and any cold cracking related to welding in heat-affected zones can create problems in an environment which promotes HIC. However, the chemical elements in the carbon equivalent equation are necessary to help meet the tensile requirements, as shown in Figure 5. Therefore, a balance must be struck between the carbon equivalent required to meet strength and that desired for improved weldability. By being able to maintain a very tight window of chemistry, both of these requirements can be satisfied. After vacuum degassing, the steel can then be cast by either bottom-poured, ingot casting or continuous casting. Previous work, also to be expanded in this paper, has shown that there is no significant difference between the two casting practices, in HIC test performance.

REVIEW OF RECENT RESULTS

Recent experience in producing steels to HIC test requirements has extended to plate thicknesses from 3/8" to 6" covering a variety of specification requirements. Because of the wealth of data that is available, certain comparisons between results can be made. The most commonly specified testing solution is the low pH solution from TM-01-77. This will be the basis of these presentations. The testing technique that is used is summarized in Figure 6. Unless otherwise specified, the testing involves three bars being immersed in the solution for 96 hours according to TM-02-84. They are subsequently sectioned for evaluation. Various ratios are then established as noted in Figure 6. The CLR (crack length ratio) is the most commonly required parameter. A grand average of 9 cross section results is used to determine the CLR_g. Recent results are summarized in Figure 7. From this Figure, it can be noted that thinner plates tend to have higher CLR_g results within the continuous cast distribution. It is also shown that the ingot cast product does not show any significant difference from continuous cast (Figure 7b compared to 7c). Another way to show this data is directly versus thickness level. This is shown in Figure 8. These results are a mixture of two different quality levels based on the 0.001% and 0.002% maximum low sulfur levels. The importance of calcium, inclusion shape control is supported by these figures. A comparison of steels produced to the two sulfur levels is presented in Figure 9.

Although CLR_g is the most commonly specified parameter, other parameters, such as CTR_g and CSR_g (grand averages) can also be required. Extension of cracking in the direction of rolling (CLR_g) is normally of the most importance. Extension of the cracking perpendicular to the surface (CTR_g) is often due to different microstructural influences which may lead to the presence of step-wise cracking resulting from the link-up of individual cracks. Figure 10 shows that even though this is the case, there is some correlation between CLR_g and CTR_g.

COMMENTS ON HIC TEST REQUIREMENTS

When HIC tested A516 steels for process vessels were initially specified, a CLR_g maximum value of 15% was the most common requirement.[4] Since that time, in an attempt to become more conservative, specifications have become increasingly more restrictive in both percentage requirement and in the way this percentage is evaluated. Figure 10 schematically shows how the samples in the

HIC test are sectioned and the subsequent averages determined. There are basically three types of numbers that can be established. For the sake of simplicity, only the CLR will be considered. The following abbreviations will be used:

CLR_g	Grand Average of nine cross-section results
CLR_s	Maximum sample/specimen/test bar average of three cross-sections
CLR_x	Individual maximum cross-section determination

The most commonly specified parameter is the CLR_g. To become more conservative, some recent user specifications are using the other two determinations. Since there is no standardized test methods for evaluating A516 steel for process vessels, each individual customer specification often takes a slightly different approach. A comparison of CLR_g and CLR_s is given in Figure 12. This figure demonstrates that there is a strong correlation between the two measurements. In general, the CLR_x value is larger than either of these determinations ($CLR_x > CLR_s > CLR_g$).

Often times, one of the nine cross-sections will have a somewhat elevated CLR_x. Normally this will be averaged out in the CLR_s or CLR_g numbers. Because of the fact that there has been no standard method established, it is inappropriate to use individual cross-section results to determine a pass or fail criteria. The current HIC test techniques that have been utilized are there to act as a sorting method of material that has been extensively processed for improved cleanliness and HIC resistance versus steels that have not. It is inappropriate that a whole heat of steel can be rejected because of the results of a single cross-section measurement. There is, furthermore, some inconsistencies on how one detects and measures a crack, that are not as important to address, when a grand average is being used, e.g., polishing and etching subtleties. Therefore, if more conservative HIC test requirements are required, specifying lower grand or specimen averages, e.g. CLR_g, CLR_s is recommended. CLR_g values as low as 5% and CLR_s values as low as 15% can be met with current technology. The overwhelming majority of customer specifications use the CLR_g as the parameter for acceptance criteria.

COMMENTS ON TEST METHOD

Considerable experience has been gained in evaluating a variety of thicknesses of material by HIC testing. When sample plates are 30 mm and less, the full plate thickness can be evaluated by the three test bars according to NACE TM-02-84. In looking at samples from plates of this thickness or less, if there is any cracking present, it can be present throughout the cross-section of the plate, but most often it is concentrated near the centerline. This is shown in Figure 13 for a number of plates of varying thicknesses.

On plates that are greater than 30 mm, it is important to take sample material across the full plate thickness. The results of the evaluation of two thick plates are summarized in Figure 14. In one case, five specimens (bars) rather than the required three were used to cover the full thickness of material. In the other plate example, 3 test specimens were removed at each test location through the thickness of the plate, thus requiring three times the amount of testing and evaluation. This amount of testing appears excessive. Often an odd number of test locations is required for thick plate evaluation. This appears to be a very prudent requirement; since it guarantees that one sample will always straddle the centerline location of the plate.

CONCLUSIONS

A review has been presented of the commercial production of HIC tested A516 steels for the last several years. The ability to produce very low sulfur and phosphorus levels to meet very aggressive HIC tested requirements has been demonstrated. HIC test results for both continuous casting and ingot cast products were presented. Correlations among various evaluation parameters have been identified. The difficulties associated with testing requirements using both grand averages, sample averages or individual cross-section requirements have been identified. The average methods were identified as being most appropriate. If there is a need to be very conservative, it is concluded that lower average requirements should be specified; comments were made upon the testing of the very thick plates.

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2. NACE Standard TM-02-84, C. 1984, Houston, Texas.

3. NACE Standard TM-01-77, C. 1986, Houston, Texas.

4. R. D. Merrick, Materials Performance, February 1989, pp. 53-55.

FIGURE 1

The Process of Hydrogen Induced Cracking (HIC)

Aqueous, Acidic, H_2S Containing Environments

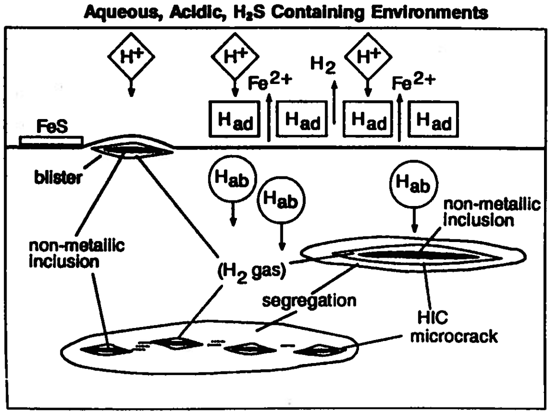


FIGURE 2

Steelmaking Process Plan

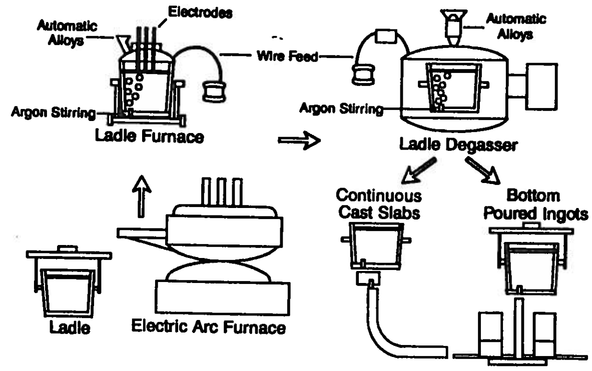


FIGURE 3

Chemistry of HIC Tested A516 Steels

Sulphur Levels

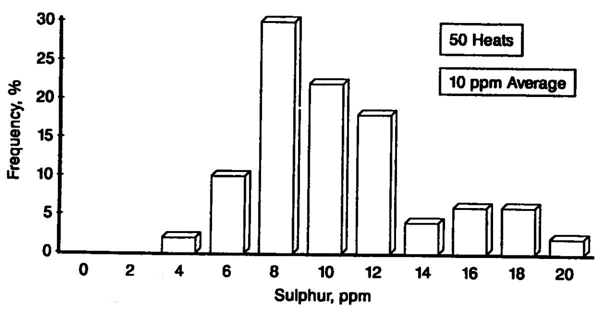


FIGURE 4

Chemistry of HIC Tested A516 Steels

Phosphorus Levels

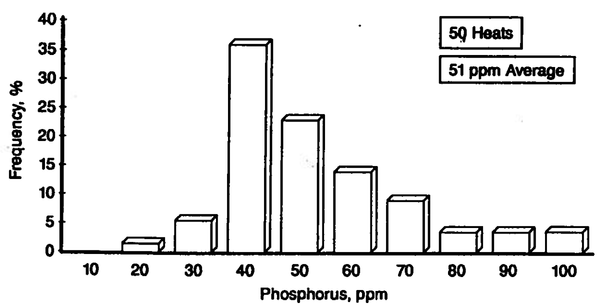
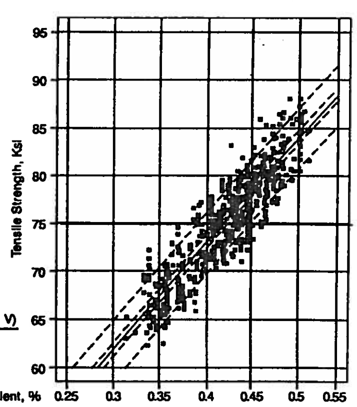


FIGURE 5

A516 Normalized Gauge Over 1.5 Inch to 3 Inch Inclusive

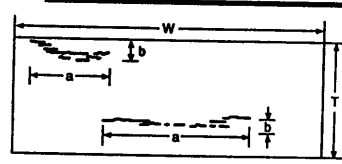
$$CE = C + \frac{Mn}{6} + \frac{(Ni + Cu)}{15} + \frac{(Cr + Mo + V)}{5}$$



Carbon Equivalent, %

FIGURE 6

Determining Hydrogen Induced Cracking (HIC) Resistance NACE Specification TM-02-84



Crack Sensitivity Ratio, CSR = $\frac{\Sigma(a \times b)}{W \times T} \times 100\%$

Crack Length Ratio, CLR = $\frac{\Sigma a}{W} \times 100\%$

Crack Thickness Ratio, CTR = $\frac{\Sigma b}{T} \times 100\%$

Where: a = Crack Length
b = Crack Thickness
W = Section Width
T = Specimen Thickness

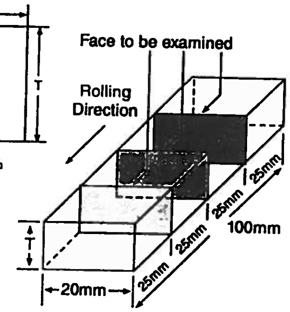


FIGURE 7a

HIC Tested Continuous Cast, A516 Steels

Thicknesses from 0.250" to 1.0"

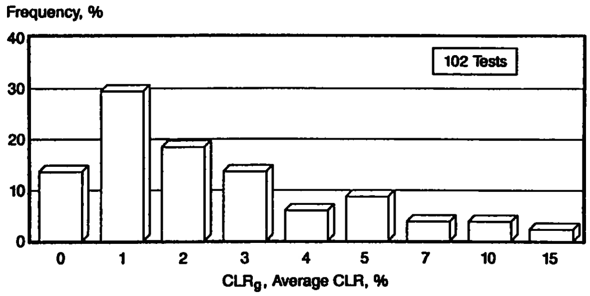


FIGURE 7b

HIC Tested Continuous Cast, A516 Steels

Thicknesses from 1.1" to 2.8"

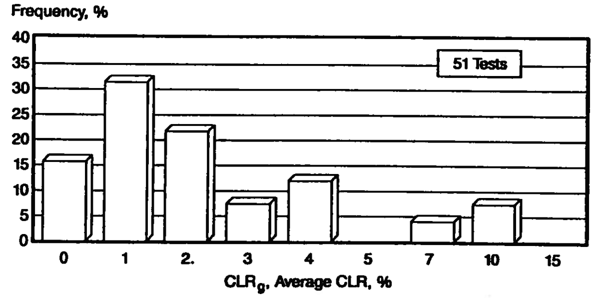


FIGURE 7c

HIC Tested Ingot Cast, A516 Steels

Thicknesses from 1.4" to 5.7"

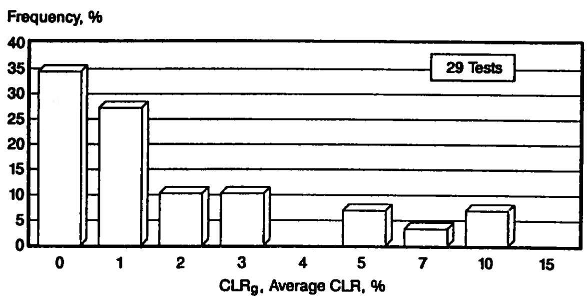


FIGURE 8

HIC Tested A516 Steels

Influence of Casting Method

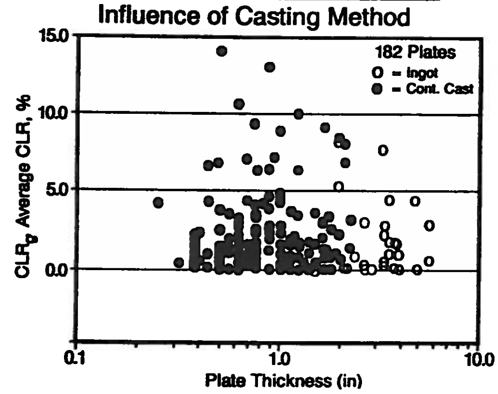


FIGURE 9

HIC Tested A516 Steels

Influence of Sulfur Level

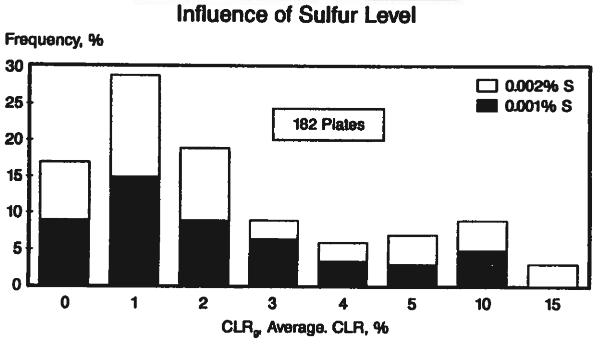


FIGURE 10

Comparison of CLR_g and CTR_g Results

HIC Tested A516 Steels

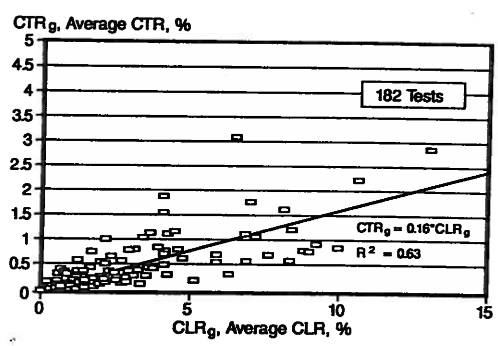
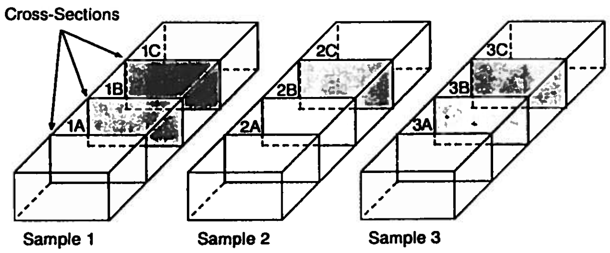


FIGURE 11

Calculation of CLR, CTR or CSR Values

Sample Average Versus Overall Average
Sample = Bar = Specimen



Sample 1 Average = (1A + 1B + 1C)/3
Overall Average = (1A + 1B + 1C + 2A + 2B + 2C + 3A + 3B + 3C)/9

FIGURE 12

Comparison of CLR Evaluation Techniques in HIC Tested A516 Steels

CLR_s (Max. Sample) vs. CLR_g (Grand Average)

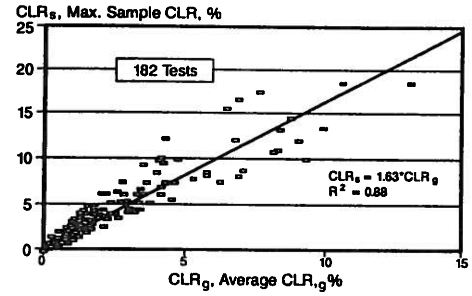


FIGURE 13

Individual Crack Lengths and Positions in HIC Test Samples

Five A516 Steel Plates

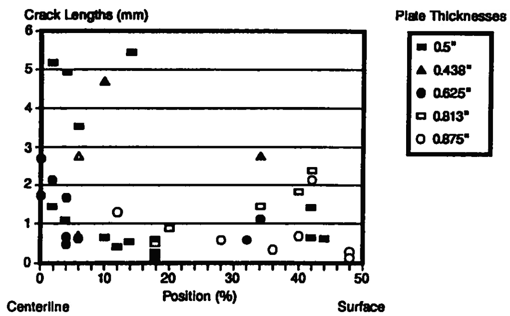


FIGURE 14a

HIC Testing of Thick A516 Plate Steel

1 Sample per Position

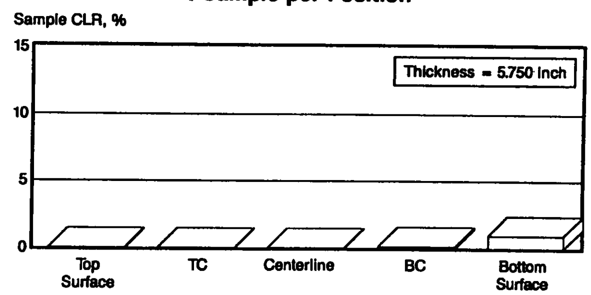


FIGURE 14b

HIC Testing of Thick A516 Plate Steel

3 Samples per Position