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The Significance of the Radiography Technique in the Non-Destructive Evaluation of the Integrity and Reliability of Cast Interconnects

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***Abstract*—**Significant changes in oil and gas drilling have emphasized the need to verify the integrity and reliability of drill stem components. Defects are inevitable in cast components, regardless of application; but if these defects go undetected, any severe defect could cause down-hole failure.

One such defect is shrinkage porosity. Castings with lower level shrinkage porosity (CB levels 1 and 2) have scattered pores and do not occupy large volumes; so pressure testing and helium leak testing (HLT) are sufficient for qualifying the castings. However, castings with shrinkage porosity of CB level 3 and higher, behave erratically under pressure testing and HLT making these techniques insufficient for evaluating the castings' integrity.

This paper presents a case study to highlight how the radiography technique is much more effective than pressure testing and HLT.

***Keywords*—**Casting Defects, Interconnects, Leak Check, Pressure Test, Radiography.

I. INTRODUCTION

THE last decade has seen significant changes in the nature of oil and gas drilling. The current state of the art in drilling and evaluation offers unique technologies to operate in complex and much more challenging wells that are characterized by deeper, hotter, and harsher environments (ex. HPHT drilling). This in turn has put greater importance and emphasis on the integrity and reliability of the drill stem components that operate in such aggressive environments. Non-destructive evaluation techniques such as radiography play a very important role in ensuring the integrity and reliability of drill stem components (wrought as well as cast components).

Interconnect assemblies are used to connect sections of an MWD/LWD tool string. Each section consists of a drill collar and a sensor to interact with the formation. Interconnect assemblies are adapted for electrical communication and fluid communication between sections of the tool string. The body of the interconnect usually has a complex profile at the neck to maintain smooth fluid flow. Depending on the casting process used to make the interconnect body; severity levels of shrinkage porosity at the neck may vary. The neck portion of the interconnect body is in close proximity with the slots and holes used for the electrical connections. If shrinkage porosity is present in excessive amounts (CB level 3 or above); pores may open up to wire-ways and cause expensive downhole failures. To avoid such failures during downhole runs; the integrity of interconnect assemblies needs to be tested before sending them to rig site. The generic industry practice is to perform pressure tests and helium leak checks to assess interconnect assemblies. However, there are inherent limitations with these tests and these methods are only adequate to qualify cast components with comparatively lower volume fractions of shrinkage porosity (CB level 1 and 2). If the shrinkage level is higher than that, results from these tests may not be adequate to reliably assess the integrity of the cast components. Hence there is a great need for an effective non-destructive evaluation (NDE) technique to use in addition to the aforementioned techniques to suitably qualify cast components used in critical applications.

Radiography is a technique that can provide the required high-quality results and help differentiate bad castings from good ones. This paper emphasizes the importance of using the radiography technique to check the integrity and reliability of cast interconnects; specifically at areas near wire ways and electrical connections. A case study is included to illustrate this point.

II. NON-DESTRUCTIVE TEST AND EVALUATION METHODS

Non-destructive testing (NDT) or non-destructive evaluation (NDE) is a discipline of engineering which deals with methods of detecting flaws in a component without distorting its profile or shape. The flaws may be discrepancies in structural properties or deformities like cracks in castings and welds; that can lead to unexpected behavior of a component. While NDT highlights the existence of a fault; NDE also measures other parameters like the size, shape, or orientation of flaws. NDT and NDE are the preferred methods for evaluating product quality as these techniques not only retain the original profile of the component being examined but are also cost-effective and reduce inspection time.

A few commonly used NDT/NDE methods in the oil and gas industry are:

- dye penetrant inspection
- eddy current inspection
- magnetic particle inspection
- ultrasonic inspection
- radiographic inspection
- pressure test

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- helium leak test

The commonly employed NDT/NDE methods listed above have been broadly classified based on the nature and location of the flaws. For surface flaw detection, the first three methods are frequently employed while ultrasonic and radiographic techniques are more suited for bulk flaw detection. NDTs such as pressure testing and helium leak testing are also employed to simulate down-hole conditions of high pressure in oil and gas drilling.

The bulk flaw detection techniques along with the pressure and leak detection techniques are the most valid for evaluating the integrity of cast components used in the oil and gas industry. Brief descriptions of these processes and their underlying principles are included in the following sections.

A. Pressure Test (PT)

In the oil and gas industry, PT is commonly performed to check the integrity of a component or a system. The test consists of multiple cycles; in each cycle pressure is applied and held for several minutes. The component is considered qualified if it does not show any sign of leakage. If the component has defects or discontinuities in its connectivity, the component may lose its ability to hold the pressure, and allow fluid into the wire-way connection. Sometimes, castings with higher severity level defects behave erratically during PT as is illustrated in the case study in section IV.

B. Helium Leak Test (HLT)

HLT is another NDT commonly used to check the integrity of components. Helium is sprayed on the component being tested (Fig. 1). If the gas leaks through discontinuities in wire-ways or ports; a sensor detects the leak, a graph displays the leakage rate of the Helium over time (in seconds), and the component fails the test.

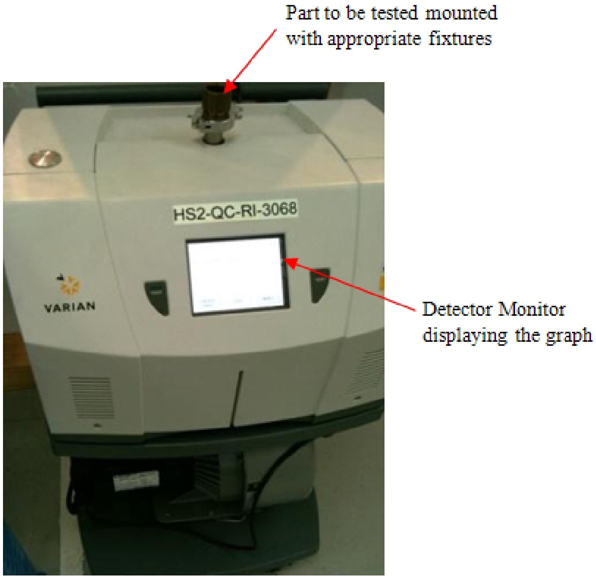

Fig. 1 Helium Leak Test equipment

C. Radiography

Radiography is an extensively used NDE technique for detecting defects in an object. It produces a 2D image of an object on photographic film. This is done by either using X-rays or gamma rays emitted by a radioactive source such as Iridium 192, Cobalt 60 etc. When the X-rays or gamma rays pass through the object; the object's material absorbs and scatters the rays; reducing the intensity of the radiation. Parameters such as object thickness, material density, and quality of radiation determine the amount of radiation lost. Therefore radiation from different sections of the object will have different intensities. The radiation emerging from the object is exposed to radiation-sensitive film so that the different shades on the film represent the different densities.

Hence a volumetric defect such as a void or a pore will have more radiation passing through them onto the film. The presence of these defects inside a cast component can be interpreted from the optical contrast on the film.

The intensity of incident and transmitted photons has the following relationship [1]:

$$I = I_o e^{-\mu t} \qquad (1)$$

Where:
I = transmitted photon intensity
I_o = incident photon intensity
μ = attenuation coefficient
t = thickness of the object

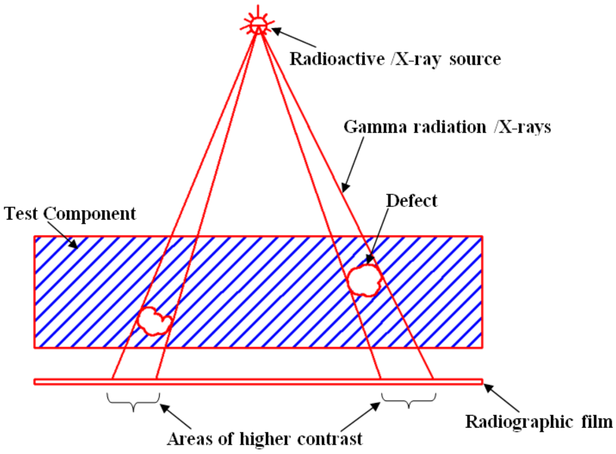

Fig. 2 Principle of radiography

III. Casting Defects and Categorization Using Radiography

Discontinuities (or defects) in an object are identified by comparing production radiographs with standard ASTM radiographs and then assigning a severity level for a particular type of discontinuity. Casting defects are grouped under several categories. For steel castings: category A is gas porosity, category B is allotted to sand and slag inclusions, and category C is assigned to shrinkage. Shrinkage is further classified as CA–for individual shrinkage strands; CB–for clustered strands; and CC–for a sponge-like appearance. As noted in ASTM E446; shrinkage type CD also exists for castings of up to 2 inches in wall thickness.

Categories A, B, and C have five levels of severity (1–5; the severity increases with the increase in number). In addition, cracks, hot tears, inserts, and mottling are categorized as D, E, F, and G respectively [2], [3]. However these categories are not further classified into severity levels. For each severity level and each category; standard ASTM radiographs are available for reference.

Defects like shrinkage occur at the end of solidification if the poured molten metal is solidified before completely filling the mold. The location of defects (especially shrinkage) also largely depends on the profile of the mold and the casting processes (mold design, gating system, how many and where the risers are located, etc).

Generally, inspection of castings, and sampling and acceptance criteria depends on the casting grade and class. The class of a casting controls the frequency of inspection; whereas the quality of casting is governed by grade [4]. However, depending upon the application and environmental conditions in which the component is used; sampling and acceptance of the castings may also be defined by the stakeholders.

IV. CASE STUDY OF AN INTERCONNECT FAILURE IN THE FIELD

One flooded interconnect assembly (drilling fluid leaked into the wire-ways) was sent from a Malaysian field location to the manufacturing facility to investigate the root cause of an electrical failure. The component was subjected to non-destructive testing and analysis that included visual inspection, dimensional check by CMM, O-ring squeeze calculations, HLT, and pressure testing. Metallurgical characterization using optical microscopy as well as electron microscopy was also performed. It should be noted that every interconnect goes through a pressure test followed by a helium leak check before they are sent to the field.

A. Visual Inspection and Dimensional Check of the Interconnect Assembly

When internal parts of the interconnect assembly were removed; traces of drilling fluid were observed which could have caused the electrical failure (Fig. 3). Further visual inspection of the interconnect revealed a deformity at the inner neck area close to the wire-way. When combined with the evidence of the drilling fluid, we suspected that there was a casting defect in the interconnect body. This defect could have been exposed after the downhole run and drilling fluid would have leaked into wire-way (Fig. 4).

Fig. 3 Leakage inside the connector

Fig. 4 Suspected casting defect area

Results of the co-ordinate measuring machine (CMM) showed critical dimensions are within the specified tolerance. O-ring-squeeze calculations verified that all the sealing parameters are within acceptable design limits and ensured that seals were not the cause of the failure.

B. HLT on Failed Interconnect

The component was tested for Helium leak with appropriate sealing and fixtures; the leak graph showed no spikes on the sensor/detector monitor (Fig. 5). Hence HLT couldn't detect any defect with the failed interconnect.

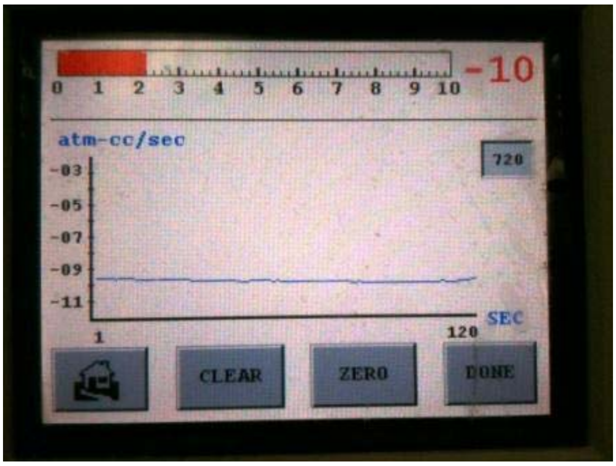

Fig. 5 Graph: Rate of Helium leak v/s time

C. Pressure Test on Failed Interconnect

The interconnect was tested three times by applying pressure of 25 ksi twice and 30 ksi once for about 30 minutes each time. We saw that the component had leaked water droplets after the pressure test fixtures were removed but that the fixtures didn't have water drops on them, indicating that the leakage probably did not occur from the fixture side (Figs. 6 and 7).

Additional pressure testing was conducted using a manual hydraulic pump. Pressure of 3000 psi was injected into the component and after about 10 minutes the pressure had dropped by 150 psi indicating a leak in the system.

As previously mentioned each of these interconnects are pressure tested as well as helium-leak tested before they are sent to the field. These functional tests are relied to detect any flaws or defects (which can cause drilling fluid to leak into wire-ways) in the interconnects. However, no bulk mapping (understanding of size, shape, orientation and location of flaw) is done using traditional NDT techniques.

The interconnects by their very nature undergo erosion at the neck areas down-hole. A sub-surface flaw (present just beneath the surface) will likely not be detected by pressure or helium-leak tests on the interconnects in their as-cast condition. However surface erosion of the interconnects might expose these flaws and then down-hole pressure would cause the interconnects to fail. Such a scenario is quite plausible and can explain the contrasting performance of this failed interconnect under pressure testing. This also means that pressure testing and helium-leak testing prior to deployment in the field are not adequate to conclusively determine the soundness of the cast interconnects.

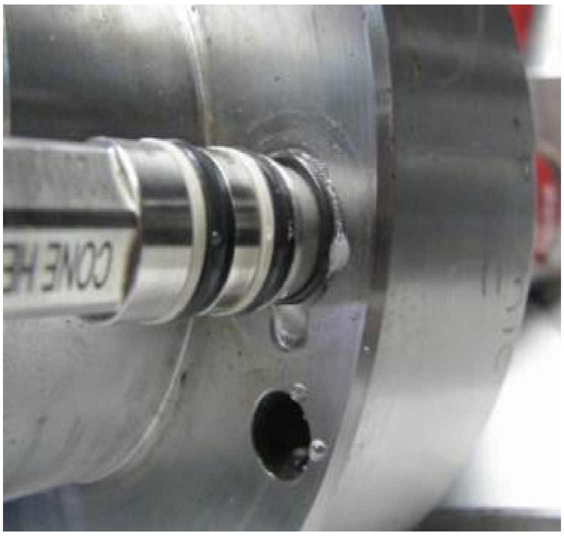

Fig. 6 Gas escapes while removing fixture

Fig. 7 Water droplets leaked deep in interconnect

D. Radiographic Inspection of the Failed Interconnect

A radiography test was conducted on the component as per ASTM standard E1742/ E1742M [5]. Iridium-192 was used as the source of the gamma rays. The images were captured on radiography films and compared with standard ASTM Radiographs E446-10 [3]. The nature and intensity of the contrasting areas on the radiographs led to the conclusion that the defect was shrinkage porosity type 'CB' and severity level '3' (Fig. 8).

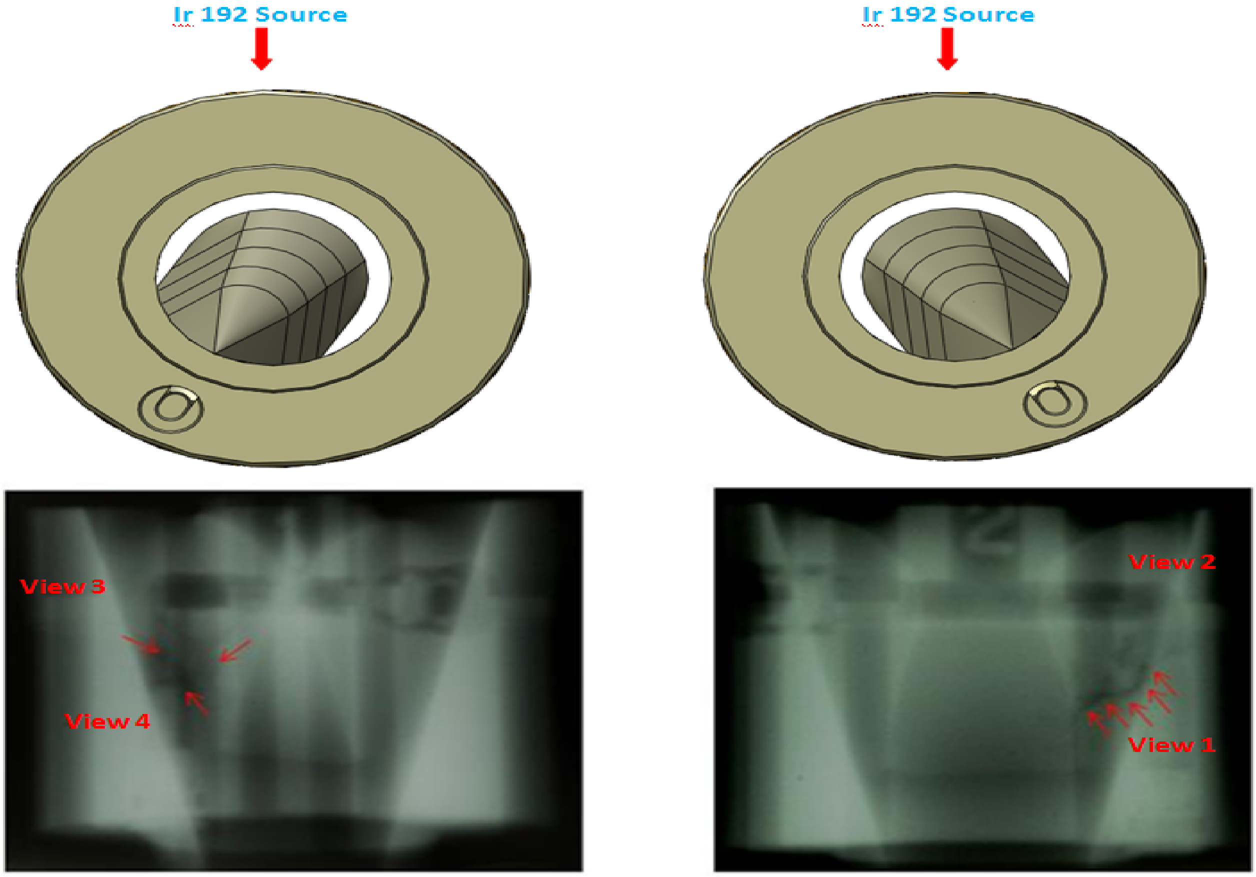

Fig. 8 Radiography test on the defect interconnect

E. Metallurgical Characterization

The component was sectioned into two halves by Electric Discharge Machining (EDM) and further metallurgical characterization studies were performed. Cross-sectional analysis near the defect location indicated a hole with brown residue surrounding it as illustrated in Fig. 9. High-resolution electron micrographs at this location indicated solidification of the dendrite structure as shown in Fig. 10. This is indicative of a shrinkage defect. Energy dispersive X-ray spectroscopy performed on the brown residue surrounding this defect indicated a significant presence of carbon, likely grease or oil residue near the defect. The shrinkage porosity was not isolated to a small area but was rather spread across the entire thickness as seen in certain cross-sectional views (Fig. 11).

Fig. 9 Cavity found at defect location

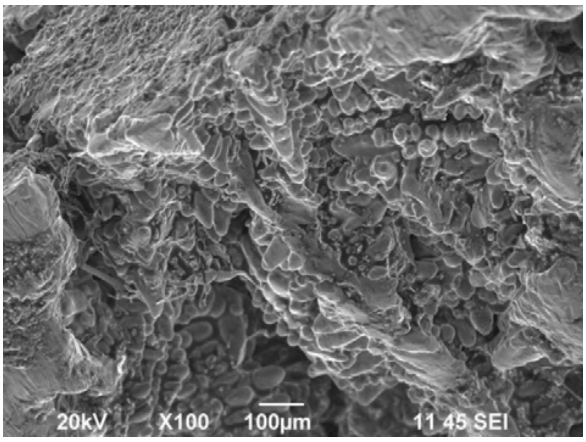

Fig. 10 Microscopic view of the dendrite structure at the shrinkage

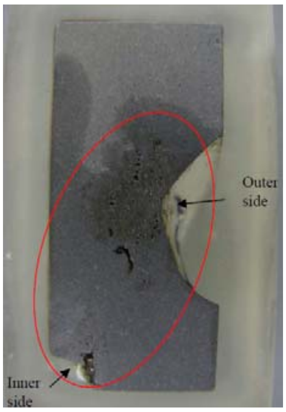

Fig. 11 Cross-sectional view illustrating the shrinkage porosity through the thickness of the interconnect wall

In summary, the metallurgical characterization identified the location of the defect and high-resolution microscopy confirmed that the defect was a result of shrinkage porosity. The shrinkage porosity was found to occupy a comparatively larger volume fraction.

F. Measures Taken after Interpreting the Radiographs

After the field failure as a result of the defective interconnects, a decision was made to send a batch of 32 interconnects for radiographic inspection to check for defective components. Two were found with the same defect as that of the one that failed in the field, shrinkage porosity of type ‘CB’ and severity level 3. Based on the radiography inspection report, the Quality department advised that the defective castings should be discarded.

Note that cast components differ from their wrought counterparts in terms of elemental segregation and the presence of defects. Cast components almost always contain defects and it is the severity of these defects that determines how effective functional tests such as pressure testing and helium-leak tests are. Since these defects are present to some degree in each casting, radiography can be effectively used to identify castings with a higher volume fraction of such defects.

Based on the radiography results, the mold design was improved by introducing a new gating system. Additionally, radiographic inspection was added to test all components in ‘as cast’ condition irrespective of their class; as testing each component is much less expensive than a down-hole failure.

V. CONCLUSION

The defective interconnect was conclusively linked to the presence of shrinkage porosity (type CB and severity level 3) which was found scattered across the defect location. These volumetric defects could not be detected using our routine qualification testing since they respond inconsistently to pressure tests and HLT. Radiography, on the other hand, can conclusively identify castings with volumetric defects like shrinkage porosity. Radiography can capture the defective connectors in the ‘as-cast’ condition (even before the final component machining) thus sparing the efforts, cost, and time required to finish machining and testing the components. The cost of qualifying each casting using radiography vastly outweighs the steep costs associated with down-hole failures. In addition, detection of such defects by radiography would provide data for analysis and design of new mold gating systems not only for interconnects but for other cast components with complex profiles. This will reduce defects in all castings used on MWD/LWD tools, which in turn will minimize down-hole failures and non-productive time.

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