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Failure analysis of metallic structures and components: part II- a case study

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This is the second of two papers dealing with failure analysis, where methodology and tools were illustrated in the first paper. In this paper, an application of the failure analysis of an oil drilling pipe is presented. A logical approach for failure analysis steps is proposed based on the available information originating from the site data, failed parts, loading records, and service conditions. The plan compromised of three basic phases; mechanical testing, chemical analysis, and stress calculations and crack propagation simulations. Mechanical testing revealed a high tensile strength steel with very low ductility, while chemical analysis proved the contamination of the inner and outer surface of the pipe with sulphur. Plane of failure for both preliminary stress calculation and crack propagation simulation under recorded failure loads, gave the same angle of inclination as observed for the failed part. Recommendations have been drawn regarding liability for the case that overloading and hydrogen embrittled pipes, concurrently accelerated failure. Also, guidelines for current pipes in use, and a proposal for prospective pipes have been suggested. This study introduces a very useful application for failure analysis procedure in such situations.

هذا البحث هو الجزء الثاني من بحثين عن تحليل أسباب الانهيار في المنشآت و الأجزاء المعدنية حيث تم عرض المنهج و الأدوات في الجزء الأول. وهذا البحث هو تطبيق ما تم توضيحه في الجزء الأول على حاله انهيار إحدى مواسير التنقيب عن البترول. وقد تم عرض طريقه منطقه لعمل التحليل مبنية على معلومات الموقع والأجزاء المنهارة من الماسورة و بيانات الأحمال لحظه الانهيار و ظروف التشغيل. وتشتمل الطريقة على ثلاث محاور أساسيه هي الاختبارات الميكانيكية والكيميائية وتحليل الاجهادات مع عمل محاكاة لنمو الشروخ عن طريق الحاسب الآلي. وقد أظهرت النتائج أن مادة الماسورة من الصلب عالي المقاومة ذو ممطوليه قليلة و أثبت التحليل الكيميائي تلوث الطبقة الصدأه في السطح الداخلي و الخارجي للماسوره بمادة الكبريت. كما أظهرت الحسابات و كذلك نموذج المحاكاة بالحاسب الآلي توافقا تاما مع اتجاه و ميل سطح الانهيار الذي تم تحديده من الجزء المنهار من الماسورة. وأتضح من تحليل أسباب الانهيار تأثر مادة الماسورة بالبيئة التي تستخدم فيها و أن تحميل الماسورة بحمل شد عالي قد عجل بانهيارها. وفى ضوء نتائج البحث قد تم وضع توصيات خاصة باجهادات تشغيل المواسير و تحديد مسؤليه الانهيار وكذلك الاختيار الأفضل لمادة المواسير المستقبلية.

Keywords: Failure analysis, Pipe, Blistering, Chemical analysis, Crack propagation

1. Introduction

This is the second paper on failure analysis with special emphasis on metallic structures and components. In the first paper, the basics of failure analysis have been illustrated, while in this paper, the application of this procedure is conducted for an actual case study. The case study considered in this paper is the failure of an oil-drilling pipe. The main theme of this paper is to show the logical steps and hypothesis of failure based on the observations and records of breakdown in site.

2. Problem description

Pipe drilling procedure involves the insertion of pipes into soil strata by rotating the pipes using special equipment. In some instants, a pipe gets stuck in a soil stratum such that it would be difficult to move it up or down from its position. In such situations, the typical field experience is to apply a tensile force to the pipe followed by applying a torque in order to be able to retrieve the pipe. This technique works well most of the time, but in some other incidences, the pipe fractures and failure analysis is required. For the case in hand, there were some concerns about the overloading of the pipe either in tension, or torsion, or both which might have led to the failure. In addition to this mechanical situation, several other aspects involved in this process exist. For instance, the suspicion of having hydrogen sulfide (H_2S) released during drilling was one of the major concerns in this case, specially if the pipes were exposed to this gas for a long time. Another factor that may have played a role in this type of failure was fatigue loading due to repeatedly using these pipes. The failed parts of the pipe have been preserved in addition to all the records at the moment of failure, particularly, the applied tensile force and torque.

With all this information in hand, it was quite difficult to come to a decision on the main cause(s) of failure. Thus, a plan of attack was prepared and transformed into several scientific steps and a thorough failure analysis has been conducted taking all these concerns into consideration.

3. Plan of attack

A plan of attack has been constructed to characterize this case study. The plan compromised of three phases; the mechanical testing phase, the chemical analysis and chemical related aspects phase, and the stress analysis phase.

The main purpose of the mechanical testing phase was to determine the mechanical properties of the pipe pertaining to the problem (i.e. yield stress, tensile strength, ductility, and hardness).

The main purpose of the chemical analysis phase was to investigate the possibility that the pipe has been exposed to hydrogen sulfide (H_2S) before, and in case of positive results, what is the concentration. This is an important aspect in explaining the failure.

The last phase is the stress analysis phase. A thorough stress analysis was conducted considering the recorded values of both torque and tension at failure together with several crack propagation simulations for failure prediction.

4. Phase I: mechanical properties

In this phase, the mechanical properties pertaining to the problem have been determined. The mechanical testing included in this phase are the direct tension testing and the hardness testing. For the direct tension tests, strips of the part of the failed pipes as delivered were cut out from the pipe wall with approximately 30 mm width and 400 mm long. Six specimens have been prepared where the sides of the specimens were smoothed to eliminate any stress concentration.

Due to the curved nature of the pipe, high stress concentration in the specimens exists at the grips of the machine. In order to minimize this effect, two 75-mm pieces of similar specimen were cut and attached to the specimen ends at the zone of gripping as shown in fig. 1. This simple procedure ensured that all the specimens failed in the middle third of the gauge length. Three specimens have been tested following this procedure. Two other specimens have been tested without attaching these parts to see the effect of the stress concentration at the grips as will be discussed later. The failure of the last two specimens was near the gripping area as expected, and their failure characteristics are of great importance.

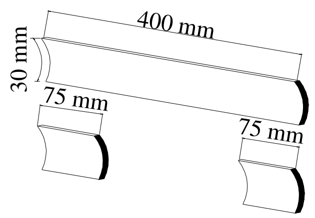

Fig. 1. End pieces to relieve stress concentration.

With respect to the hardness test, both Brinell hardness testing and Rockwell hardness testing have been conducted. For Brinell hardness test, a 10 mm ball was used as an indenter with a load of 3000 kg., while a 5 mm ball with 150 kg. was used for Rockwell hardness test.

4.1. Test results

Results for the direct tension and hardness testing are given in table 1. Results indicate that the average ultimate tensile strength of the three specimens was 846.7 MPa, with an average elongation of 6.12%. This indicates that the pipes are of high strength steel. There was no yielding associated with any of the tested specimens. On the other hand, hardness tests revealed average values of 279 and 84 for Brinell and Rockwell hardness numbers, respectively.

4.2. Comments on the mechanical properties results

Regarding the direct tension test, the main feature of all the specimens was the disappearance of yield stress. The failure of all the specimens was associated with very little plastic deformation that is reflected on the ductility of the material as represented by a relatively small percentage of elongation.

The test results of the original pipes are not available for comparison in order to determine whether this brittle behavior was observed before the exposure to the severe environment or not. However, the very low ductility of the three specimens, in addition to the disappearance of yielding suggest that this brittlement is associated with the severe environment as will be shown later. Regarding the hardness tests, results indicate relatively high values for both Brinell and Rockwell tests.

5. Phase II: chemical analysis and chemical related aspects

In order to determine the possibility of pipe exposure to hydrogen sulfide, the corroded layers at the inner and outer surfaces of the pipe have been chemically analyzed for sulfur. Results indicate that the weight percentages of sulphur on the outer and inner surfaces of the pipe are 0.28 and 0.348 % respectively. It should be mentioned here that the a considerable amount of the surface layer containing the sulphur has been lost due to the handling and transportation of this part of the pipe in addition to the machining operations (cutting, etc.). All these factors have contributed to the loss of the very thin corroded layer.

It is quite important to understand how this service condition (the existence of hydrogen sulfide) may affect the properties of the pipe material; especially it is made of high strength steel as revealed by the mechanical testing. Thus, a condensed literature on the effect of this hostile environment is presented in the next sections. This part is of crucial importance as it explains part of the failure causes of the pipe, the observed fracture surface, and the recommendation for future aspects regarding existing and prospective pipes.

5.1. High tensile strength steel in hostile hydrogen sulfide environment

High strength steel is in great demand for its high strength to weight ratio, thus it has widespread applications in many fields. Due to its high strength, the allowable design loads for structures made of high tensile steel is quite higher than normal strength steel. Unfortunately, with the increase of the steel strength, other material properties tend to decrease, particularly, its ductility. The increase in design loads, and consequently working tensile stresses, with a considerable reduction in ductility lead the steel to become more susceptible to brittle fracture, especially under hostile environments. The existence of these hostile environments assists in increasing the potential of what is usually referred to as Stress Corrosion Cracking (SCC) [1].

The impression of inherent brittleness of high strength steel due to the formation and propagation of cracks is the main visible manifestation of stress corrosion cracking. Generally, cracks propagate with a little attendance of macroscopic plastic deformation despite the fact that the steel prior to exposure to such hostile environment usually conforms to normal ductility standard. In summary, the combination of sufficient tensile stresses and the hostile environment, together with specific metallurgical requirements, in terms of composition of the alloy, may contribute to the formation and propagation of cracks in steels, resulting in a brittle type of failure [2].

Table 1
Mechanical properties of pipe material

Specimen No.	Dimensions mm	Yield stress MPa	Ultimate strength MPa	Elongation %	B.H.N.	R.H.N.
1	29.3x8.55	-	822.3	6.0	284,284,	83, 83, 84,
2	29.3x8.6	-	843.7	5.9	269	84, 85
3	27.9x8.7	-	874.2	6.45	av.=279	av.= 84

Failure of high strength steel components by the formation and propagation of cracks (brittle fracture) has been encountered in many fields with a wide range of environments. Examples include oil, aircraft, petrochemical, and many others. It is a well-established phenomenon that most of the fracture type failure of high tensile steels are associated with stress corrosion cracking especially in hostile environments and mostly are due to what is called "hydrogen embrittlement". The form of embrittlement may be hydrogen induced blister formation or hydrogen induced cracking. The ease with which hydrogen can be picked up from aqueous environment makes this type of embrittlement the most recognized with high strength steel [2]. Although other stress corrosion cracking processes may exist, however, these processes are rarely of a practical problem for high tensile steel.

5.2. Hydrogen embrittlement of high strength steels

Basically there are two mechanisms through which hydrogen can enter steel, the gaseous or the aqueous phase. In the former, which represents the case in hand, the reactions involve the adsorption of molecular hydrogen (or other gases such as hydrogen sulfide). This process is followed by the dissociation of hydrogen molecules to produce hydrogen atoms adsorbed to the surface followed by subsequent diffusion of the adsorbed hydrogen atoms into the metal lattice. The crystalline structure of the metal surface is distorted due to the presence of hydrogen atoms resulting in surface solubility which is higher than that of the bulk. It is most probable that the distorted zone may play the major role in initiating the brittle fracture behavior despite the fact that the depth of this distortion cannot be determined exactly [2].

The location of hydrogen atoms in the iron lattice is usually associated with two sites. The first is the tetrahedral site and the second when hydrogen atoms are strongly attached to defect sites in the lattice known usually as "traps" [2]. These traps include vacancies, grain boundaries, voids, nonmetallic inclusions, and alike. The trapping of hydrogen in voids may be in the form of adsorbed hydrogen on the walls of the void and with molecules hydrogen in the void itself. With steel in contact with acidic solutions containing hydrogen sulfide very high pressure can develop in the voids (in some cases, more than 10^5 atm) [1,3]. If this is combined with the hydrogen embrittlement of the steel around the void, it results in the initiation and propagation of cracks giving what is called "blistering" as described in the first part of these two papers. It is worth mentioning that remarkably small concentration of hydrogen (less that 1 ppm) can cause this type of embrittlement in high strength steel [6]. Also, hydrogen embrittlement has been observed in high strength steel in contact with gaseous hydrogen even at pressures below 0.001 atm. which means that there is no need for high pressure for the occurrence of this phenomenon [2]. Furthermore, the presence of iron sulfur has a catalytic effect in increasing the amount of hydrogen that enters the steel [4].

5.3. Effect of hydrogen on steel mechanical properties

The effect of hydrogen on elastic modulus is very limited and by far the most crucial effect is on its ductility. Hydrogen embrittlement is the main cause of failure of high strength steel in service even at stress level considered safe under normal service condition (no hostile environment). The fracture toughness of steels exposed to hydrogen has shown considerable reduction in value. It is now well-established that the higher the steel strength, the more potential of hydrogen embrittlement, the more the damaging effect on the fracture toughness, leading to brittle behavior [2].

6. Characterization of the observed fractured surface

The most significant characteristic of the fractured surface of the failed drilling pipe is the disappearance of attendant macroscopic plastic deformation. This eliminates the possibility of reaching the yielding of the metal and leaving brittle fracture mechanism the only one associated with this type of failure.

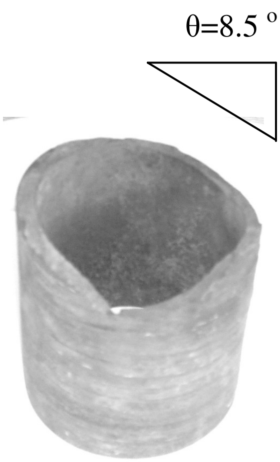

Fig. 2. The inclination angle of the fractured surface.

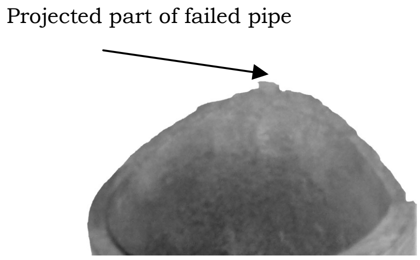

Fig. 3. Hydrogen blistering of the pipe.

The failure surface has an inclination angle of approximately 8 to 9º as shown in fig. 2 indicating that the main cause of failure is associated with axial stresses in the long direction of the cylinder.

The second step in the elimination process is the fatigue crack growth. Typical character of fatigue crack growth is discussed in the first part (i.e. beach marks), which has not been observed in the fractured surface. It has been noticed that the surface is irregular and rough that means that the main cause of failure is crack propagation from certain defect. By examining the small part projected from the failed surface, it was noticed that there is some form of blistering as shown in fig. 3. On the other hand, one of the specimens tested in the direct tension test, without the end parts where stress concentration is high due to machine gripping, showed the type of failure shown in fig. 4. This type of failure is associated with blistering as well. All these observations play the dominating role in failure analysis.

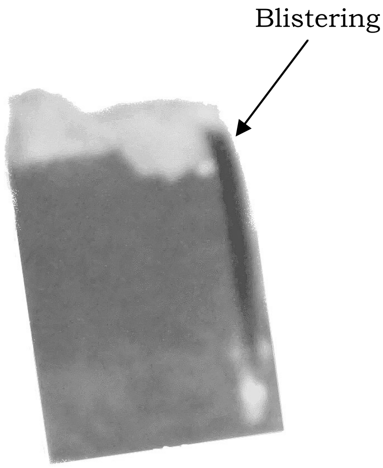

Fig. 4. Hydrogen blistering as observed in testing.

7. Phase III: stress analysis

7.1. Preliminary stress calculations

Simplified stress calculations for the stress state in the drilling pipe at the moment of failure were conducted. As reported in the records, the tensile force and the applied torque acting on the pipe were: T=1.2 MN and M_t= 10170 N-m, respectively, as shown in fig. 5. The measured internal diameter of the pipe was 110 mm. The average thickness of the pipe wall was 8.66 mm. Under this loading condition, the axial tensile stress σ_x =372 MPa, and the shear stress τ_{xy} =56.67MPa. Thus, the principal stresses were found to be; σ_1 = 380 MPa and σ_2 = -8.4 MPa, where the angle of inclination for the principal axis was 8.477º

7.2. General remarks on the preliminary calculations

1. The tensile stress due to pulling the pipe is quite high, although the ultimate strength is about 846.7 MPa Yet, this working stress for a pipe in service with the hostile surrounding environment is questionable.
2. Shear stress is adequate and small compared to axial tensile stresses
3. The combination of both shear and tension does not have a significant effect on the principal stress compared to the tensile axial stress.
4. The inclination angle of the principal stress direction to the horizontal = *8.47º* which is

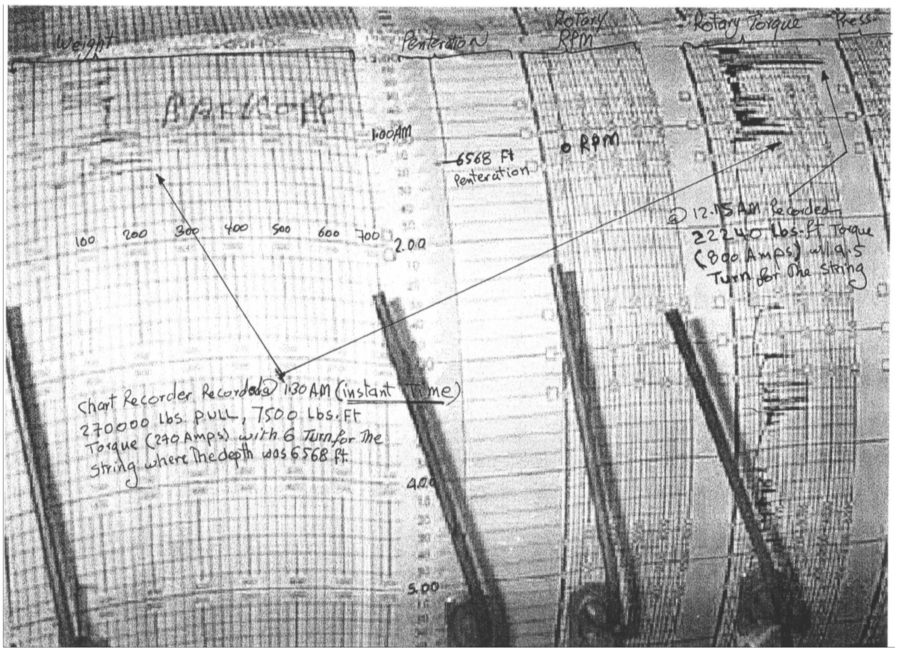

Fig. 5. Records of tension and torsion at failure.

very close to the angle as measured in the failed specimen.
5. Although the principal stress is quite high, however, in normal conditions this will not cause failure (Strength/stress ratio= 2.226). Thus other factors should be considered in the failure analysis.

7.3. Numerical simulation of crack propagation

A numerical simulation of crack propagation in the pipe has been conducted using a special finite element package for crack propagation using remeshing technique. The program uses standard eight or six node serendipity elements with quadratic shape functions [5]. For the original mesh, the eight node element was used, while for remeshing, the six node element was generated automatically around the crack tip. These elements perform well for elastic analysis and crack propagation as well [5, 6]. The crack propagates in the direction predicted using the propagation theory of the sigma theta max theory [7], For crack propagation simulation, the well-established remeshing technique is utilized [8] in which the geometry of the crack is represented explicitly at each crack propagation step to reflect the current crack configuration. The automatic remeshing strategy adopted in this study is to delete the elements in the vicinity of the crack tip, move the crack tip, and then insert a trial mesh to connect the new crack to the existing mesh using triangulated elements.

The material properties used in this investigation are elastic modulus of 196 *GPa*, Poisson's ratio of 0.3, and fracture toughness of 60 $MPa\sqrt{m}$ which reflects the induced brittleness due to severe exposure condition. In order to investigate the crack propagation and orientation, an initial crack length and orientation should be assumed first. The loads acting on the pipe as considered in this simulation are those straining action recorded at failure (i.e., $T=1.2\ MN$ and $M_t= 10170\ N\text{-}m$).

Three different cases are considered for this loading values, in all cases, the initially assumed crack length = 1.0 cm. However, for case (1), the orientation of the crack was 0^o, i.e. horizontal crack. For case (2), the initial crack was oriented at 45^o to the horizontal, while for case (3), the orientation was -45^o. Fig. 6-a through 6-c show the crack orientation after propagation and the enlargement of the finite element mesh around the propagating crack. It is clear that irrespective of the initial crack length orientation, numerical simulations show the same orientation of the final crack propagation (around 8 to 9°). This finding is very important as it coincides with the plane of principal stresses in the preliminary stress analysis, and the observed plane of failure as well.

Another interesting case is case (4) which represents the case of very high torque of Mt= 52159 *N.m* and relatively lower tensile force T= 0.24 *MN*. In this case, the shear stresses due to torque dominate the failure mode and the inclination of the failure surface will be close to the 40° as shown in fig. 6-d. This type of failure has been observed before in some other cases of failure in the same field condition.

8. Main causes of failure and failure mechanism

Based on the information presented in the previous sections, the main causes of failure for the case in hand can be summarized. Most of the observations and analysis lead to the strong believe in the occurrence of hydrogen embrittlement in the pipe due to the exposure to hydrogen sulfide. Chemical analysis has shown the existence of sulfur traces in the corroded outer and inner layer of the pipe. The mechanical properties of the pipe material showed high strength steel with very little ductility. Also, the failure shape as shown before in fig. 3, which represents hydrogen blister, leads to a strong believe that the pipe was embrittled by hydrogen. The applied tension force at failure was too high resulting in high tensile stresses in the pipe. The

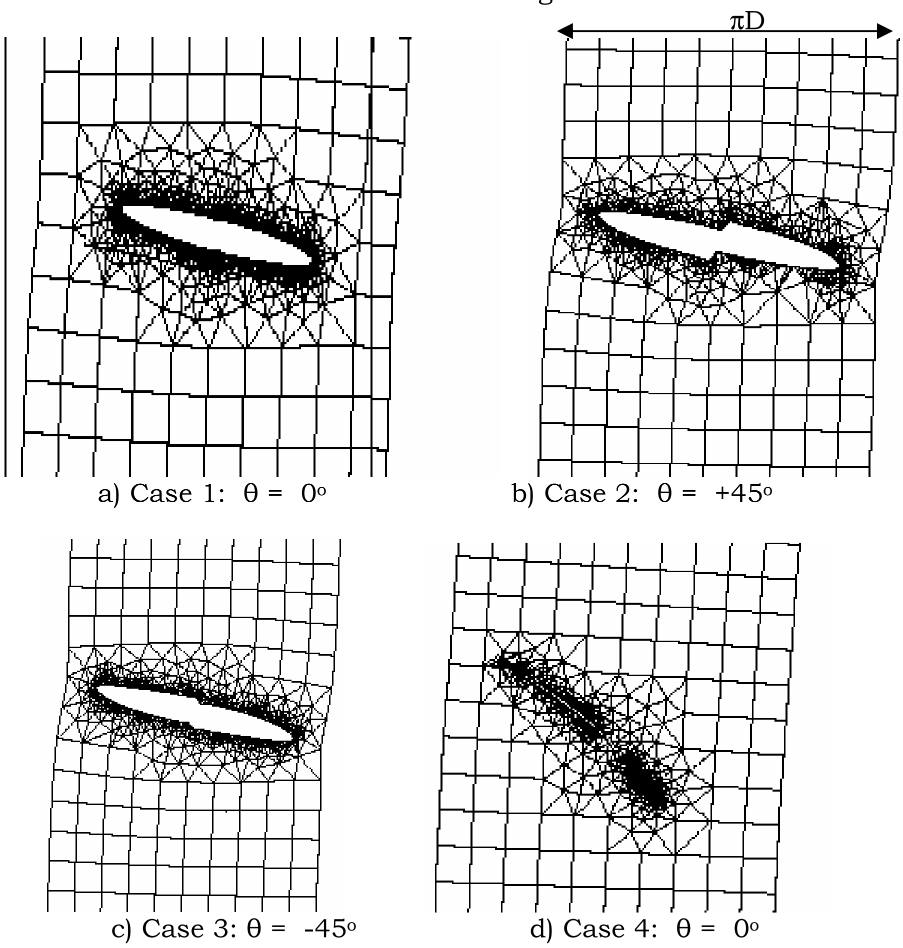

Fig. 6. Numerical simulation of crack propagation.

existence of any defects in the pipe wall or a hydrogen blister had led to the initiation of a certain crack with any random orientation. Due to the high stress intensity factor imposed by the high tensile stresses, in addition to the considerable reduction in fracture toughness owing to hydrogen embrittlement, the stress intensity factor at the crack tip reached a critical value and the crack started to propagate. The propagation of the crack, as observed from the fractured surface, was inclined 8 to 9^o to the horizontal, meaning that the main cause of stress intensity increase was the tensile force in the pipe direction. The same angle of inclination is also obtained during preliminary stress calculations, and numerical crack propagation, which supports the hypothesis that the axial tensile load played the dominant role in the failure of the pipe. However, as crack continued to propagate, the ligament of the pipe (i.e. the remaining uncracked part of the pipe) was not aligned with the applied force at the other end of the pipe. This led to very large eccentricity between the applied load and the resisting ligament. High bending stresses at both ends developed and with more crack propagation, both the eccentricity and the bending moment increased until the complete failure of the pipe. This explains the bending of the pipe at the other end of it far from the fractured surface as shown in fig. 7. This concludes the failure mechanism and the main causes of failure. It is very important to explain that the high tensile stresses applied to the pipe, hydrogen embrittlement, and hydrogen blistering were the main factors for the failure. However, the pipe would not have been failed, if lower tensile stresses were applied. The high tensile stresses accelerated the failure of the pipe.

9. Conclusions

Based on the failure analysis conducted in this paper for the failure of an oil drilling pipe in service, the following conclusions can be drawn:

1. Traces of sulphur have been found on the outer and inner surface of the fractured pipe, suggesting the exposure of the pipe to hydrogen sulfide in service.
2. The percentage of the sulphur has been found to be of small concentration (0.28% for the outer surface and 0.34% for the inner surface)
3. Although the concentration of the sulfur in the corroded layer inside and outside the pipe is very little, it is enough to release hydrogen gas concentration causing the hydrogen embrittlement as documented in the literature and explained before.
4. The pipe material is found to be of high strength steel which is mostly susceptible to hydrogen embrittlement.

Fig. 7. Photo of the other end of the pipe after failure.

5. The applied loads (tension and torsion) at the moment of failure showed a magnitude of principal tensile stress of 380 MPa.
6. Visual inspection of the fractured surface eliminates the fatigue type of failure and substantiated the idea of brittle fracture.
7. Blistering phenomenon associated with hydrogen embrittlement have been observed for the failed pipe and during experimental testing supporting the theory of failure proposed.
8. There is a high possibility, supported by the finding in this research, that the main cause of failure is the combination of high tensile load in addition to the hydrogen embrittlement.
9 Failure could have been postponed if the applied tensile load were lower than that recorded at failure.
10. Simplified stress analysis, observed failure surface, and numerical simulation of crack propagation with different initial crack orientation led to the same inclination of failure surface suggesting the appropriateness of the hypothesis.

Recommendations

Based on this failure analysis case, the following can be recommended:

Regarding the existing drilling pipes: As the service conditions can not be avoided (especially the exposure to hydrogen sulfide), and since coating of the pipes for corrosion protection is impractical, the only option is to limit the applied loads in case of the pipe getting stuck and since all pipes are already contaminated with hydrogen and suffering from hydrogen embrittlement, the safety factor for the service loads should be increased to lessen the probability of failure due to the combination of high tensile stresses and hostile environment.

The tensile strength/actual stress as recorded in the case in hand is 2.14 at failure. If this safety factor is increased to 5.0 this will lead to safer service condition resulting in a maximum tensile pulling force of 0.317 MN, with a corresponding torque of *10170 N-m.* It should be noted that this limitation will not prevent further failure; however, it will postpone the failure leading to longer life span of the existing drilling pipes.

Regarding new pipes: The use of steel types with dense microstructure (*face-centered-cubic "fcc"*) is essential in the cases where hydrogen exist as they are more resistant to hydrogen embrittlement [1,2]. Examples for this family of steels include austenitic steels such as stainless steels from, the 300 series. The (*fcc*) structure of austenite is inherently more ductile than the (*body-centered-cubic "bcc")* ferrite, and thus less liable to switch to brittle behavior in the presence of hydrogen. Also, the use of killed steel greatly increases the resistance to hydrogen blistering because of the absence of voids in this material [1]. Nickel-containing steels and nickel-base alloys have very low hydrogen diffusion rates and are often used to prevent hydrogen blistering.

It is worth mentioning that upon the choice of the appropriate new material, appropriate tests such as the National Association of Corrosion Engineers (NACE) test method TM-01-77 for sour (hydrogen sulphate) environments should be conducted to determine the acceptability of the alloy [9].

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