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Case study

Failure analysis of a leaked oil pipeline

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ABSTRACT

An oil pipeline embedded in an underground trench had failed. Through the accident investigation we found that there was a perforation at the leak point of the pipeline. Macroscopic observation revealed that some pits collectively located at the exterior surface of the failed pipeline. In addition, raised ridges and circumferential cracks were observed inside the large pits with stereoscope and scanning electron microscope. After careful analysis it is concluded that the leakage of the pipeline was mainly caused by the liquid impingement erosion.

1. Introduction

Liquid erosion is one type of wear that is the progressive loss of original material from a solid surface due to mechanical interaction between the surface and a fluid in a very small area. This can be further classified into two types: i.e., the cavitation erosion and the liquid impingement erosion. The cavitation erosion is usually caused by the formation and collapse of cavities or bubbles within the liquid. In engineering practice, lots of machines and structural components suffer cavitation damages, which makes cavitation erosion become very active research topic all the time [1–7]. However, the liquid impingement erosion, which originates from the impact by liquid drops or jets, has been rarely reported as the dominated reason [8–10]. Actually, in most of previous failure cases, the liquid impingement erosion often appears together with corrosion [11–16].

In this work, failure analysis of a leaked oil pipeline was carried out. Through careful macroscopic and microscopic observations, the leakage of this pipeline was found to be fully caused by the liquid impingement erosion. The pipeline is made of one kind of low-carbon steel, and its wall thickness is 4.5 mm. The pipeline was located in an underground trench that is covered by cement boards, and had been used for about ten years. In addition, while it was usually empty in the pipeline, some oil with temperature of ~80 °C could flow through the pipeline during the period of the equipment maintenance.

2. Visual observation and experimental procedure

Two pipe samples cutting from the failed pipeline are shown in Fig. 1. Apparently, it can be found that some pits locate on the exterior surface of the both two pipes. Furthermore, in one pipe sample, a perforation can be found inside one large

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Fig. 1. Examples of the failed pipes. The leak point is indicated by the white arrow.

pit, which is also one leak point of the pipeline, as indicated by the white arrow. No perforation was observed in another pipe.

Chemical analysis was performed to examine the composition of the material. Then, in order to conveniently observe and analyze the failure mechanism, the failed pipes were cut into small samples from the positions near the pits and the perforation using a wire electrical discharge machining (WEDM) method. A stereoscope and a LEO Supra 35 scanning electron microscope (SEM) were used to observe the pits macroscopically and microscopically, respectively. Energy dispersive spectrometer (EDS) analysis was performed to determine whether there are some other elements inside the pits. Furthermore, with the method of grinding and polishing, a metallographic section plane of one large pit was made and observed by SEM, to further examine the morphology of the pit.

3. Experimental results

3.1. Chemical composition analysis

The failed pipes had been initially designed to be made of low-carbon steel. The chemical compositions of the as-received pipes were examined by chemical analysis, and the results are shown in Table 1. In order to determine whether the material of the pipeline was qualified or not, the national standard values of the compositions were also listed in Table 1 for comparison. Clearly, the compositions are in consistent with the standard.

3.2. Macroscopic observation

The macroscopic morphology of the pits and the perforation were observed by the stereoscope, as shown in Fig. 2. Comparing Fig. 2a with Fig. 2b, three common features can be found. First, both two damaged sites show the aggregation of pits. Second, in each pit-aggregation, there is always a large pit, as indicated by the red arrows. Third, around and inside the large pit, many small pits with different size can be observed. However, the differences between the morphologies of two damaged sites are also evident. For example, for the pipe sample showed in Fig. 2b, all pits seem to be

Table 1
Chemical compositions of the as-received pipeline.

Chemical compositions								
C	Si	Mn	Cr	Ni	Cu	P	S	Fe
Testing value (wt%)								
0.21	0.24	0.45	0.031	0.034	0.12	0.010	0.008	Margin
The national standard of chemical compositions (wt%)								
0.17–0.23	0.17–0.37	0.35–0.65	≤0.25	≤0.3	≤0.25	≤0.035	≤0.035	Margin

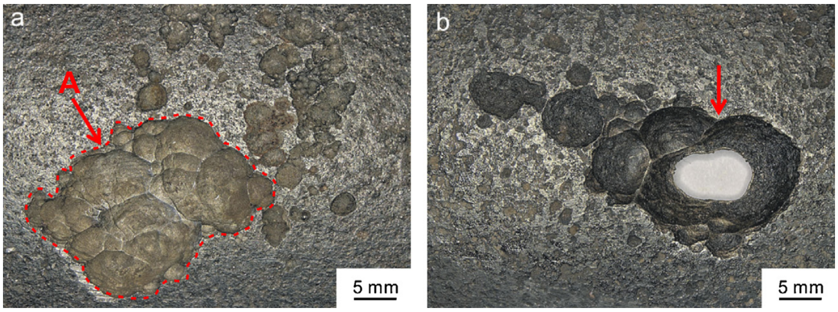


Fig. 2. Macroscopic morphology of two pipe samples observed by stereoscope, showing the pits and the perforation. The large pit in each sample is indicated by the red arrow.

deeper than those pits in Fig. 2a, and the largest pit had already penetrated through the wall of pipe, resulting in an obvious perforation, while no perforation can be observed in Fig. 2a.

3.3. SEM observation

The sample with pits shown in Fig. 2a, especially the large pit marked as "A", was further observed by SEM. The results are displayed in Fig. 3. Fig. 3a shows that inside the large pit "A" there are multiple small pits. These small pits contact or even overlap each other, and collectively form the large pit. Note that the black patches indicated by the red arrows should be adhesive dirt that was supposed to be cleared away. Fig. 3b presents the local amplification of the boxed area in Fig. 3a. Convex ridges are obviously visible, indicated by the blue arrows. Furthermore, near the large pit "A", many smaller pits can also be observed (Fig. 3c), well agreeing with the above macroscopic observation. In addition, a crack with approximately circular shape was found, as indicated by the yellow arrows in Fig. 3d. Thus it can be deduced that a new pit would be formed if this crack extended to be closed along the ring and the materials surrounded by the crack peeled off. Also, a circumferential

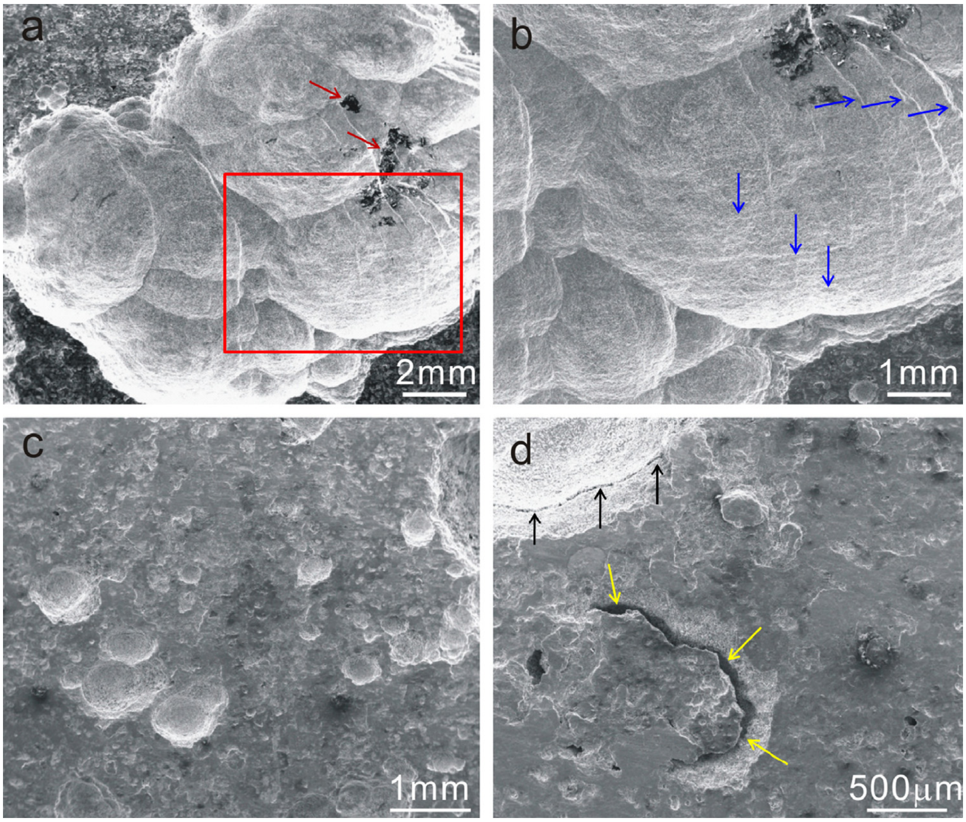
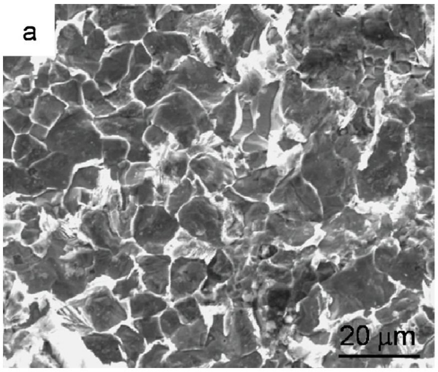


Fig. 3. SEM observations on the pits in the pipeline: (a) the low-magnification observation; (b) local enlarged image of the red boxed area in (a); (c) small pits near the large pit; and (d) circumferential cracks as indicated by the arrows.



b

Element	Weight %	Atomic %
C K	11.58	34.51
O K	5.53	12.37
Fe K	82.89	53.12
Totals	100.00	100.00

Fig. 4. Results of EDS analysis on the large pit: (a) the SEM image showing the zone for analysis; and (b) the corresponding EDS results.

crack was found at the boundary of the pit "A", as indicated by the black arrows in Fig. 3d, implying that a small pit might probably be formed inside this pit "A" when this crack were closed circumferentially.

3.4. Energy dispersive spectrum analysis

In order to find out inside the pits whether there are some other elements besides the original ones of the material, the composition at the location shown in Fig. 3b was analyzed by EDS. Fig. 4a shows an enlarged image of Fig. 3b, at which the EDS analysis was performed. The corresponding numerical results of element content are shown in Fig. 4b. No corrosive elements, yet a small amount of oxygen, were detected. In other words, the pipe should have experienced slight oxidation, but no corrosion.

3.5. SEM observation on the metallographic section plane of pit

To further observe the internal morphology of the large pit "A", a metallographic section plane was made, and then observed by SEM. Fig. 5a shows the low-magnification image of the metallographic section plane. One can see that the internal surface of the pit is not smooth, but rather uneven, as can also be more clearly seen in the enlarged local image (see Fig. 5b). Further examination of the internal surface shown in Fig. 5b reveals many small pits with size ranging from micro scale to sub-millimeter scale, which is in good accordance with the SEM observations in Section 3.3.

4. Discussion

Macroscopic observation showed that all damaged sites with aggregations of the pits appear on the exterior surface of the failed pipes. As the leak point of the pipeline, a perforation was observed, which was probably caused by the penetration of pits through the wall thickness of pipeline. These results suggest that the formation mechanism of the pits on the exterior surface of the pipes should be directly relevant to the leakage of the pipeline.

Firstly, the pits on the pipes should not be caused by mechanical damage, because there are no any traces of mechanical collision on the external surface of pipes. Secondly, the EDS analysis did not find any corrosive element on the internal

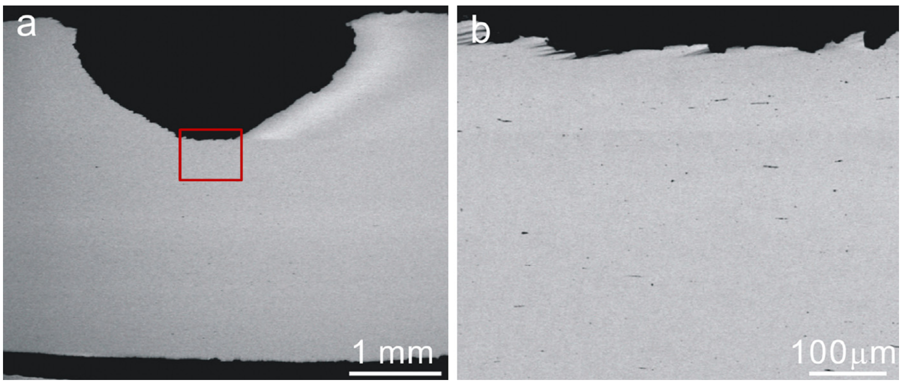


Fig. 5. SEM observations on the metallographic section plane of the pit "A" in Fig. 2a: (a) low-magnification observation; (b) local enlarged image of the red boxed area in (a).

surface of the pit, indicating that the pits should also not be attributed to corrosion. Then how did these pits form? According to the results of macroscopic and microscopic observations, the characteristic morphology feature of the pits should be the various pit sizes, that is, many small pits can be observed inside and/or near the large ones. Supposing the smallest pit resulted from single injury to the exterior surface of the pipe, the large pit should be caused by multiple injuries. SEM observation on the metallographic sectional plane demonstrates that the internal surface of the large pit is uneven, well consistent with the multiple injuries for the formation of the large pit. In addition, discontinuous circumferential cracks inside and near the large pit "A" were observed (Fig. 3d). It can be deduced that new pits would be formed if these cracks extended to close and the materials surrounded by the circumferential cracks peeled off. If more damages were introduced, the large pits would penetrate through the wall thickness of the pipe to form a perforation, eventually giving rise to the leak of the pipe. Therefore, based on the above results and discussions, the pits on the surface of the as-received pipes should not stem from mechanical damage or corrosion, and they must be formed gradually in a process that includes multiple injuries to the exterior surface of the pipeline.

According to the introduction of the accident, the local weather was rainy heavily for a few days before the finding of the leak. The investigation in the scene of the accident also found rainwater in the underground trench, where the failed pipeline was placed. It implies that there should be some holes or gaps at the joints between two adjacent cement boards. This can

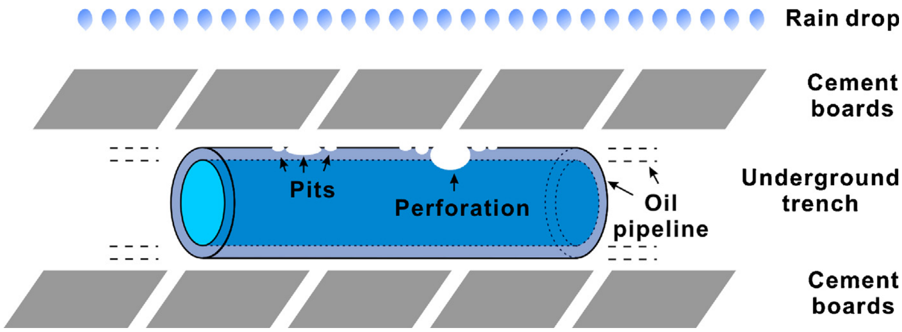


Fig. 6. Schematic diagram of the failure locations and the surrounding environment of the failed oil pipeline.

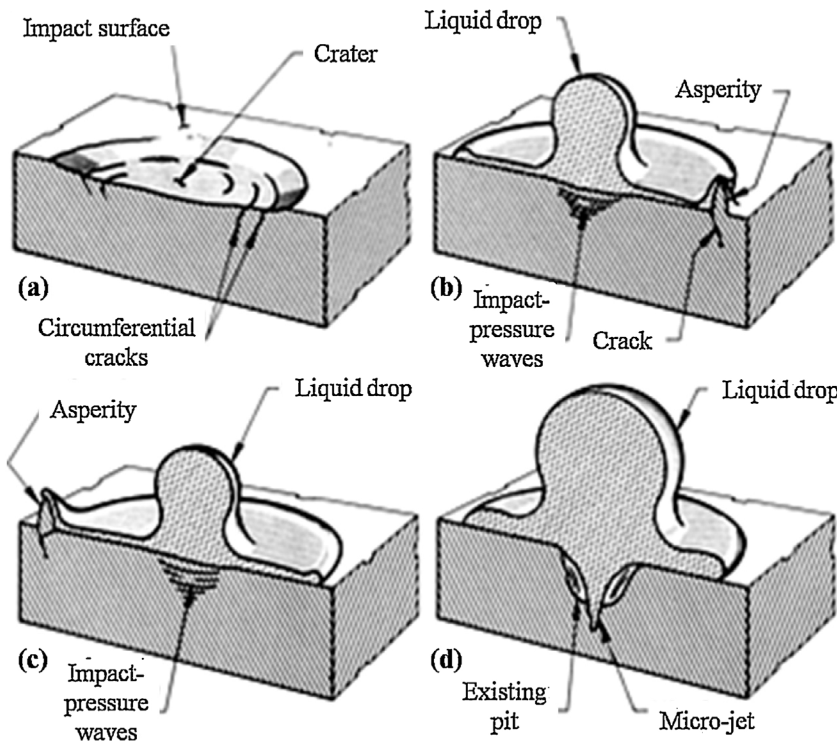


Fig. 7. Processes of materials' damage by liquid impingement erosion [17]: (a) solid surface showing the initial impact of a liquid drop that produces circumferential cracks or shallow craters; (b) high-velocity radial flow of liquid is arrested by a nearby surface asperity, at the base of which cracks are initiated; (c) subsequent impact by another liquid drop breaks the asperity; (d) direct hit on a deep pit results in accelerated damage.

probably cause the direct impact from the raindrops on the exterior surface of the pipeline, and consequently resulting in the formation of the pits and perforation, as illustrated in Fig. 6. These situations demonstrate that the leak of the pipeline should be attributed to the liquid impingement erosion induced by falling raindrop.

In order to further examine our predictions, the mechanism of liquid impingement erosion is discussed. In the handbook of *Failure Analysis and Prevention* [17] published by American Society for Metals (ASM), a model for the liquid impingement erosion was proposed, as illustrated in Fig. 7. According to this model, the erosion should be caused by continued impingement of liquid droplets. During the impact of liquid on the sample surface, the impact-pressure induced by the moving liquid can produce some circumferential cracks, or shallow craters or both, depending on the ductility of the material (Fig. 7a). Apparently, the craters are prone to form in the very ductile materials, while the circumferential cracks are expected to be preferentially observed in brittle materials but can also be found in ductile materials after repeated impact and plastic deformation. Following the impact, the liquid flows away rapidly along the radial direction. The flow of liquid would be blocked by some surface asperities or steps that may be formed by plastic deformation during the impact. Consequently, a crack is easy to produce at the base of surface asperities or surface steps (Fig. 7b and c). In the present investigation, key evidences supporting this model were found. First of all, the morphologies of the damage and the leakage of pipes are all pits and/or the aggregation of pits, which provides evidences for erosion. What's more, the different size of the pits as well as the large pit containing small pits demonstrates that the pits were formed by a number of repeated impacts, in good accordance with the continued impingement of liquid droplets in the model. Besides, convex ridges, which correspond to the surface asperities or steps, were found inside the pit (Fig. 3b). Moreover, a circumferential crack was also observed inside the large pit (Fig. 3d), consistent with the impact induced cracking at the exterior surface. Finally, the material of the pipeline is low-carbon steel that has a good plastic deformability, which makes the formation of tiny pits very easy and also well explains the uneven feature of the internal surface of the large pit. Consequently, the liquid impingement erosion can be confirmed to be responsible for the leakage of the pipeline.

5. Conclusions and suggestions

Based on the experimental observations and the analysis above, it can be concluded that the failure of the oil pipeline should be originated from the liquid impingement erosion induced by falling raindrop. Thus, suggestions to prevent the recurrent of the accident may include: (1) Adding water-proof coating or cover to avoid the direct exposure of the external surface of the pipeline, which may be also beneficial for averting other types of erosion and corrosion; (2) keeping the underground trench always dry; (3) periodically checking the covered cement boards, and ensuring no locally large holes. The present work provides sufficient experimental evidences for liquid impingement erosion, which may be helpful for future engineering failure analysis.

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