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## Effect of Local Corrosion Caused by Inclusions and Surface Scratches of Steel in High Temperature and Pressure Flue Gas Environment

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# Effect of Local Corrosion Caused by Inclusions and Surface Scratches of Steel in High Temperature and Pressure Flue Gas Environment

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**Abstract.** By simulating the high temperature and high pressure flue gas environment in heavy oil thermal recovery, the influence of two kinds of surface defects, steel inclusions and surface scratches, on local corrosion of steel was studied. And the mechanism of local corrosion caused by inclusions and surface scratches was analysed steel #20 and 26CrMo4 were used as experimental materials, and reacted in a 9 MPa flue gas environment for 24h. The reaction temperatures were 120 °C and 250 °C. The results show that the non-metallic inclusions in the steel are weak parts of the passivation film on the surface of the sample and are easily corroded by corrosive media. The scratched area is more likely to cause aggregation of corrosive media than other parts of the steel surface, and the iron elements in the metal in this area are more likely to reach the surface and react with the corrosive medium.

## 1. Introduction Formatting the text

These Steam assisted gravity drainage technology is the most commonly used enhanced recovery technology in thermal recovery of heavy oil. Steam is injected through horizontal injection wells. The heated heavy oil flows along the gas cavity wall to the production well and is produced under the action of gravity. In the practical application, it is found that the steam assisted gravity drainage technology may lead to the problems of large steam consumption and low heat energy utilization rate<sup>[1-2]</sup>. Therefore, the technology of flue-steam assisted gravity drainage is developed. The flue-steam assisted gravity drainage technology can effectively enhance the oil recovery and improve the economy of oil recovery compared with the single steam injection<sup>[3]</sup>.

In the process of injecting steam into a heavy oil thermal recovery well, the casing is subjected to a biggish compressive stress due to thermal expansion. Because of the relaxation and creep of metal materials, the casing is subjected to large tensile stress, and the casing bears such high tension-compression stress periodically in the process of stopping injection oil production. This causes fracture (or threaded joint slippage), deformation and casing damage in thermal recovery wells<sup>[4]</sup>. The thermal stability of ordinary American Petroleum Institute(API) casing such as N80 steel casing is poor under the condition of heavy oil thermal recovery. The Cr-Mo series low alloy steel is used as tubing material in 26CrMo4 casing, which makes the casing have good thermal stability, so it is widely used in heavy oil thermal recovery. At the same time, Steel #20 is widely used in surface pipeline.

In the oil and gas field industry, the fracture of carbon steel and alloy steel under stress and corrosion environment is one of the most dangerous forms of failure. The localized corrosion of passive metals almost always begins with the local presence of impurities, especially inclusions, as



well as grain boundaries, dislocations, crack defects or mechanical damage. At present, the corrosion of steel caused by inclusions has been widely discussed<sup>[5-8]</sup>. However, there are few studies on the corrosion of casing caused by inclusions and scratches in high-temperature and high-pressure flue gas environment. In this paper, 26CrMo4 and steel #20, which are widely used in heavy oil thermal recovery, are used as experimental materials. It is of practical significance to study the corrosion law of inclusions in high temperature and high pressure flue gas environment.

## 2. Experimental

### 2.1. Material and Pretreatment

The experimental materials were steel #20 and 26CrMo4, and the chemical composition thereof is shown in Table 1. The corrosive medium is flue gas, and its composition is shown in Table 2.

**Table 1.** Chemical compositions of the tested steels.

Steel	C	Si	Mn	Cr	Mo	P	S	Ni	Fe
#20 (wt.%)	0.18	0.21	0.42	0.22	-	0.02	0.033	0.22	Bal.
26CrMo4(wt.%)	0.24	0.23	0.81	0.92	0.21	0.02	0.03	-	Bal.

**Table 2.** Chemical compositions of the corrosion fumes.

Gas	O <sub>2</sub>	CO <sub>2</sub>	NO <sub>2</sub>	H <sub>2</sub>	H <sub>2</sub> S	N <sub>2</sub>
Vol.%	7%	11%	0.005%	0.001%	0.001%	Bal.

The steel #20 and 26CrMo4 were respectively processed into 8mm×8mm×5mm and 6mm×6mm×6mm hexahedral samples by wire cutting. Before tests, the six surfaces of the sample were polished to the mirror surface with 200 mesh, 800 mesh, 1500 mesh sandpaper to remove the outermost dirt and oxide layer. The oil on the surface of the sample is removed with acetone, and then the surface of the sample is rinsed with distilled water and placed in absolute ethanol to prevent oxidation of the material. The samples were taken out and dried with cold air and then wrapped with filter paper after all the samples were polished and cleaned. The accurately measured weight was taken after placing it in the drying dish for one hour.

### 2.2. Experimental method

The reactor is a tube furnace with a furnace tube size of  $\varnothing 12 \times 600$  mm provided by Kejing Company. Before the experiment, the tube furnace was first filled with high-purity nitrogen for 2 hours to remove oxygen. The sample is placed in the middle heating section of the tube furnace and the mixed gas fed into the furnace tube to make the pressure inside the tube reach 9 MPa. The reactor was set the program to a temperature of 120°C and 250°C. The sample was taken out of the reactor after 24h and washed 3 times with distilled water and absolute ethanol. The experimental conditions are shown in Table 3.

**Table 3.** Chemical compositions of the tested steels.

Run No.	Sample	Temperature (°C)	Pressure (MPa)	Reaction time (h)	Corrosion medium
1	Steel #20	120	9	24	Flue gas
2	26CrMo4	120	9	24	Flue gas
3	Steel #20	250	9	24	Flue gas
4	26CrMo4	250	9	24	Flue gas

### 2.3. Characterization of the Corrosion Scale

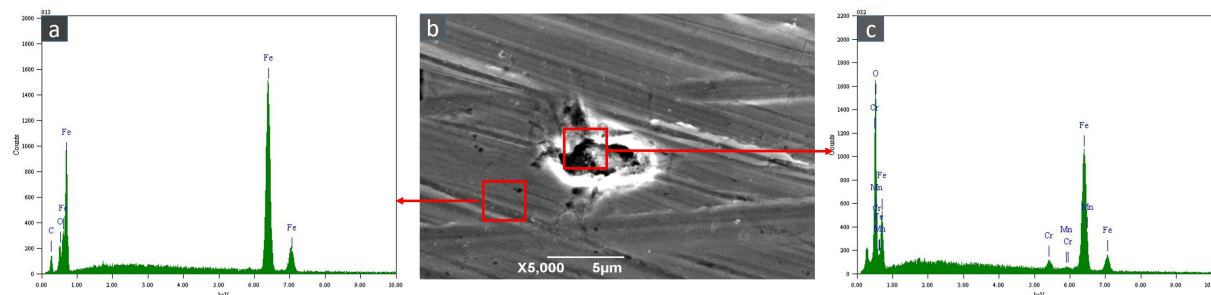
The surface of the corrosion scales were observed using scanning electron microscope (SEM). The elemental compositions of the corrosion scales were analyzed using energy dispersive spectroscopy (EDS).

### 3. Results and discussion

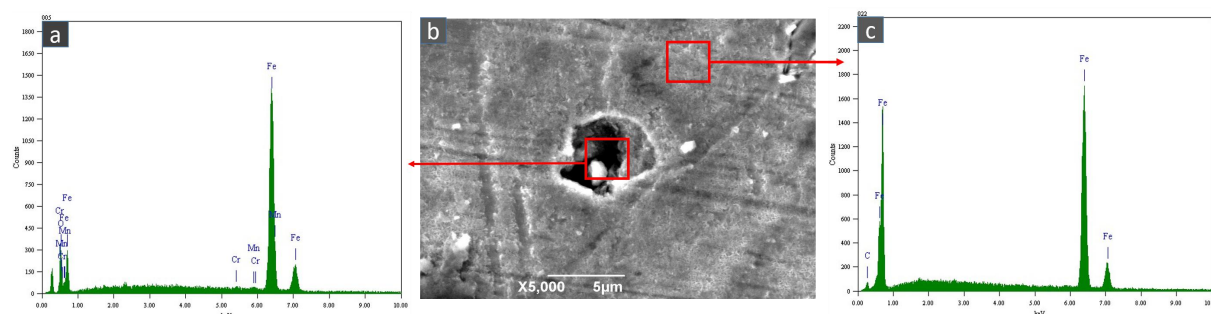
#### 3.1. Effect of inclusions on corrosion

The presence of inclusions can lead to chemical homogeneity on the surface of the sample, resulting in weak areas in the passivation film formed on the metal surface, including the boundary between the metal matrix and the non-metallic inclusions and the chemically active inclusion itself.

Sulfide inclusions are the most sensitive locations for initiation pitting of carbon steel and low alloy steel. In carbon steel, there are usually mixed Fe-Mn sulfides. The manganese-rich sulfide is easily corroded by corrosive medium, and a manganese-rich sulfide is easily attacked by a corrosive medium. Cracks are often formed around manganese-rich sulfides, and inclusions and matrix are eroded. The steel #20 and 26CrMo4 used in this experiment all contain a certain proportion of impurity elements such as Mn, S and P. This is unavoidable in the iron and steel smelting process. These materials are trapped inside the material during the formation of the metal, forming defects in the crystal. If some of these impurities are exposed during the polishing process, local defects will occur. These defects are active sites where corrosion preferentially occurs, resulting in corrosion pits. The observation of the morphology after the corrosion test did show some local corrosion aggravation behavior caused by inclusion defects. However, through the observation of the morphology after the corrosion test, it is true that some localized corrosion behaviors caused by inclusion defects exist on the surface of the sample. Figure 1 and figure 2 shows the morphology of the inclusions due to localized corrosion of inclusions in the experimental samples.



**Figure 1.** SEM and EDS images of steel #20 for 24h at 9MPa and 120°C:(a) EDS images of uncorroded area, (b)SEM images of sample surface,(c) EDS images of corroded area.



**Figure2.** SEM and EDS images of 26CrMo4 for 24h at 9MPa and 120°C:(a) EDS images of uncorroded area, (b)SEM images of sample surface,(c) EDS images of corroded area.

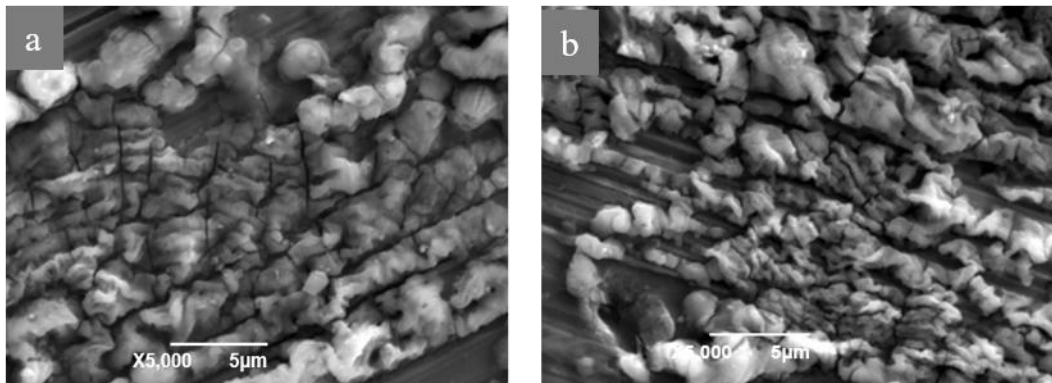
There are two explanations for the mechanism of steel corrosion caused by inclusions. One is that pitting occurs and developed in the micro-voids on the boundary between sulfide and metal, and the other is pitting caused by the dissolution of sulfide itself. In particular, certain composite sulfide-oxide inclusions establish a disordered state in the region immediately adjacent to them, therefore affecting the protective properties of the passivation film. At the same time, the locally disordered film is thick but often defective. The adhesion of the film is generally poor, and the physical and chemical resistance is low.

It is worth noting that the occurrence of localized corrosion caused by inclusions has little to do with the temperature, pressure and corrosion time of the experiment. The position of inclusions in the sample block cannot be predicted. The morphology of the inclusions is exactly in a certain area of the observed surface, and the surface is not covered by a thicker corrosion layer.

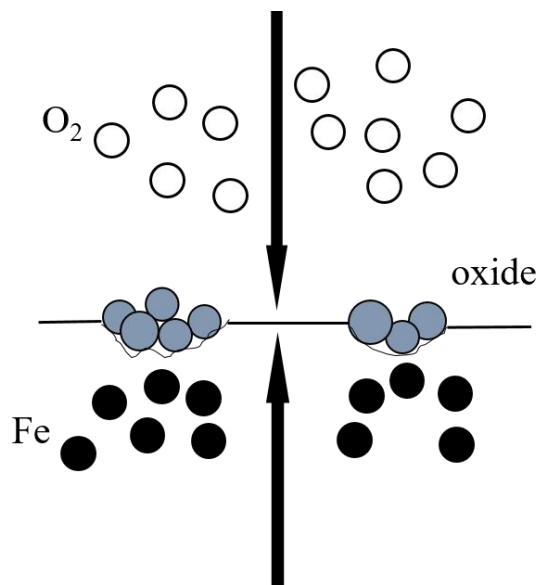
### 3.2. The effect of scratch on corrosion

The scratch is a groove left on the surface during the sanding of the sample, which determines the roughness of the surface. Methods for the rough treatment of surfaces include electrolytic polishing, grinding, pickling, and mechanical polishing. In this experiment, the surface of the sample was treated by sandpaper on the mechanical polishing of the material according to the corrosion test standard, so that scratches will be left on the surface of the sample.

In this experiment, the sample was carried out under high temperature environment of corrosion of 9MPa and 250 ° C. As shown in figure 3, such corrosion product particles grown along the scratch were observed. After 24h reaction time, there were three different morphologies on the surface of steel #20 and 26CrMo4 samples, which were flat surface, scratches and corrosion product particles growing along the scratches. At the same time, the energy analysis shows that the corrosion product is iron oxide.



**Figure 3.** SEM images of corrosion for 24h at 9MPa and 250°C:(a) steel #20, (b)26CrMo4.



**Figure 4.** Schematic diagram of corrosion mechanism at scratch.

The local corrosion mechanism caused by scratches on the surface of steel is shown in figure 4. Scratched depressions provide a natural enrichment site for the enrichment of corrosive media. Since

the sunken region is closer to the substrate, the iron ions diffused outward from the substrate are first brought into contact with oxygen ions adsorbed on the metal surface in these regions and undergo oxidation reaction to form a corroded particle product. The diffusion path of iron element in the matrix includes two channels, the grain boundary and the inner part of the crystal, wherein the diffusion speed at the grain boundary is higher than the diffusion speed inside the crystal. And a large number of scratches appearing on the surface during polishing can become a diffused short-circuit path. The high temperature environment helps to increase the diffusion rate and the size of product particles. This process should be more obvious in high temperature environment and occurs in the early stage of corrosion. As the corrosion progresses, the scratches will gradually be covered and the oxide growth advantage in the scratch direction will no longer exist.

#### 4. Conclusion

In this paper, the corrosion of two common steel surface defects such as inclusions and scratches on steel surface in high temperature and high pressure corrosive media environment is studied. Carbon steel and alloy steel usually have mixed Fe-Mn sulfide inclusions. Sulfide is susceptible to corrosion by corrosive media, and a gap is formed around it, causing both inclusions and matrix to be corroded. Scratches and inclusions of materials are relatively close to the metal matrix and also become corrosive medium enrichment areas. Therefore, in order to improve the service life of the gas injection pipeline, it is necessary to avoid defects such as inclusions, scratches and mechanical damage on the steel surface in practical applications.

#### Acknowledgments

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