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In situ observation of deformation and failure behavior in the burn-through instability zone of in-service welding

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Abstract. Based on the in-situ high-temperature SEM and laser scanning confocal microscope (LSCM), the high-temperature plastic deformation and failure behavior of X65 pipeline steel at 1000℃ and 1200℃ were studied in this paper, and the strain evolution behavior in this process was analyzed by DIC technology. In this study, the precipitation and dissolution of carbide at the austenite grain boundary were observed during the in situ heating process. The external load showed a great effect on the growth of the grains, and the grains grew rapidly by swallowing each other. The grain size, material performance, and misorientation played an important role during the deformation and crack evolution. At high temperatures, cracks were mainly initiated and propagated in the position with a large plastic strain. The strain concentration showed a significant effect on crack initiation.

Keywords: in-situ SEM; in-situ LSCM; DIC; deformation and failure behavior.

1. Introduction

In-service welding ensures the continuous operation of the pipeline, which is an environmental, economic and efficient oil and gas pipeline repair technology and also an important development direction of pipeline repair [1]. Due to the forced constraint of the pipeline and the existence of a flowing high-pressure medium in the pipeline, there are two main technical difficulties for in-service welding: 1) burn-through instability 2) hydrogen cracking. Among them, burn-through instability is the primary problem to solve [2].

In essence, burn-through instability is a high-temperature deformation and failure behavior under multi-field coupling. Burn-through instability should undergo dynamic processes such as the initiation and evolution of micro-defects, the connection and expansion of defects, and the formation of macroscopic defects (burn-through pinhole and crack). The burn-through instability is a highly complex problem involving many phenomena, including melting pipe wall metal, high temperature, stress and strain evolution, metal strength reduction, radial deformation, defect initiation and evolution, pinhole and crack. Based on the consideration of engineering value, previous studies mainly focus on the evaluation criteria of in-service welding. The previous criteria mainly include the minimum wall thickness criterion [3], inner wall maximum temperature criterion [4, 5], residual strength criterion and plastic failure criterion [6]. It can be found that all the failure models are based on the phenomenon and mechanism of in-service welding failure instability, but there is still a lack of research on the plastic deformation and failure mechanism of burn-through instability.

It is found that there are a large number of microcracks near the burn-through pinholes in the burn-through instability zone. The previous research on burn-through instability is mainly based on failure analysis. There is still a lack of the in-situ characterization of high-temperature deformation behavior and failure mechanism. Compared with in-situ experimental results, in-situ high-temperature monitoring test can capture the dynamic evolution process of material failure and is an indispensable test technology to study the dynamic evolution behavior of the burn-through instability. In-situ SEM combined with high-temperature tensile equipment, EDS, EBSD, and other equipment can analyze deformation and failure behaviors below 1200℃.

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Based on in-situ SEM equipment, Swathi et al. [7] studied the deformation mechanism of Alloy 709 at different temperatures (25℃-950℃). It was found that the deformation mechanism of Alloy 709 at low and medium temperature (<650℃) was mainly dominated by slip. At high temperature, the micro-defects initiated before the slip band, and the connection and propagation of the micro-defect was the root cause of material failure. With the help of in-situ SEM equipment [8], the high-temperature deformation mechanism of nickel-based superalloy was studied. In-situ high-temperature digital imaging technology (DIC) could capture the dynamic strain evolution and distribution in the process of high-temperature deformation. Based on in-situ DIC and numerical simulation, shang et al [9] found that the crack preferentially initiated in the softened recast layer and expanded along the softening phase. It was also found that there was an obvious stress and strain concentration at the crack tip.

Based on the in-situ high-temperature SEM and laser scanning confocal microscope (LSCM), the high-temperature plastic deformation and failure behavior of X65 pipeline steel at 1000℃ and 1200℃ were studied in this paper, and the strain evolution behavior in this process was analyzed by DIC technology.

2. Experimental procedure

The test material is X65 pipeline steel, and the chemical composition and mechanical properties are shown in Table 1 and Table 2, respectively.

Table 1. Chemical compositions (in wt%) of X65.

Material	C	Si	Mn	S	P
X65	0.12	0.45	1.85	0.025	0.015

Table 2. The mechnical properties of X65.

Material	tensile strengh (MPa)	yield strength (MPa)	Elongation (%)	Charpy impact energy (J)
X65	571	476	⩾26.5	255/230/220

In situ LSCM system comprises optical microscope, in situ stretching equipment, and a heating chamber. Its heating temperature ranges from 50 to 1200℃, and its effective heating area is about 50 mm * 10 mm. The test device can apply a constant load or constant displacement rate on the sample with drive speeds of 0.01 to 20 mm / min. The effective test stroke of this equipment is about 80 mm. The material specimen was clamped on the in situ tensile table, and the sample was heated to 1100℃ with a heating rate of 200℃/s. After that, the sample was held at 1100℃ for 1 min and then loaded at a speed of 1mm/min. The deformation and fracture behavior were observed during this process.

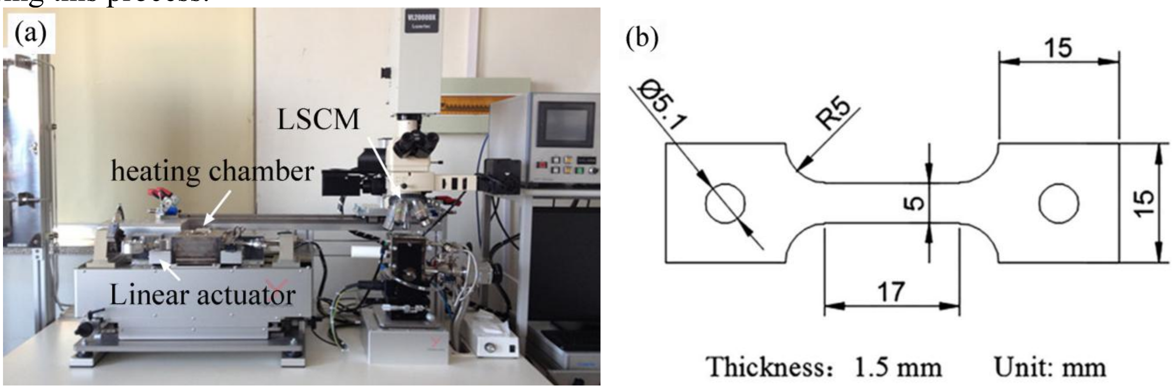

Figure 1. Laser scanning confocal microscope system
(a) LSCM and loading system (b) Sample size.

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On this basis, in situ SEM tensile test at 1200℃ was carried out. The test system was composed of in situ tensile table, heater, control system, and mechanical sensor. The SEM was TESCAN S8000, and the in-situ heating system was MINI-HT1200-SE. The sample was corroded by 4% Nital. After that, it was put into the heating chamber and heated to 1200℃ at a rate of 0.6℃/s. Then the uniaxial stretching was applied to the sample with a strain rate of 1 μm/s. During this process, strain evolution was obtained.

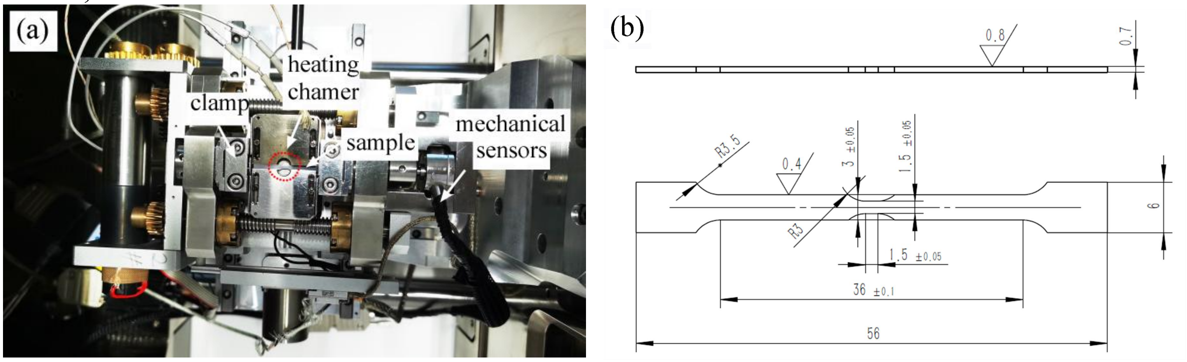

Figure 2. In-situ SEM tensile test equipment (a) experimental system (b) sample size.

3. Results and discussions

Figure 3 showed the change in the sample surface during the heating process. When the load was 0 N, the initial state of the sample was shown in Figure 3 (a). It could be seen that the sample surface was smooth, and the sample preparation was good. When the temperature rose to 753.3℃, austenization appeared, and the grain boundary was relatively obvious. When the temperature rose to 932.2℃, a large amount of carbide began to precipitate near the original austenite boundary, and when the temperature continued to rise to 1000.2℃, the precipitated carbide began to redissolve.

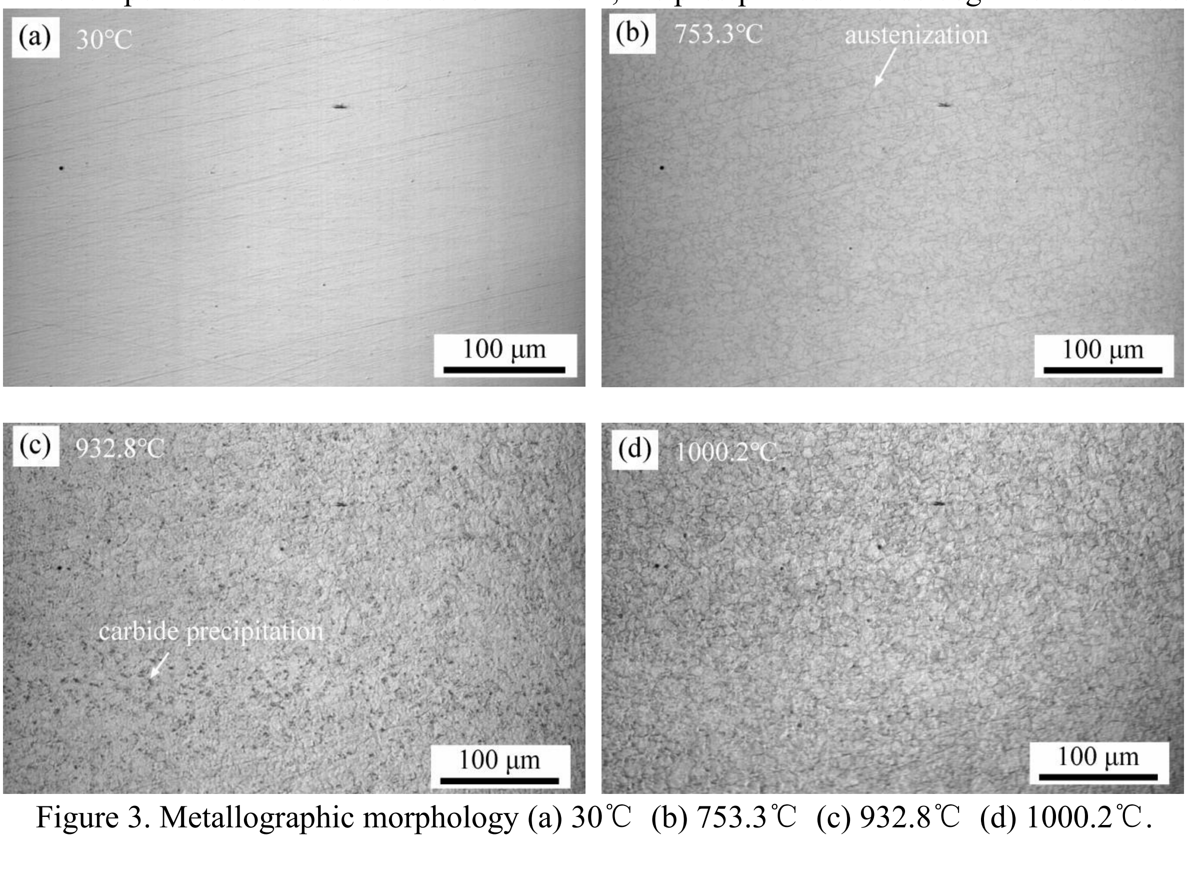

Figure 3. Metallographic morphology (a) 30℃ (b) 753.3℃ (c) 932.8℃ (d) 1000.2℃.

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The material deformation and failure process was shown in Figure 4. As shown in Figure 4 (a) and (b), the external load showed a great effect on the growth of the grains, and the grains grew rapidly by swallowing each other. When the load was applied to 144N, some of the grains grew significantly. At the same time, grain size became uneven and the slip band and intergranular crack were found. According to Figure 4 (d-e), coordinated deformation became very hard between some grains. It was easier to produce plastic deformation and cracks in the p1, p2 and p3 area. The plastic deformation behavior in the early stage was mainly dominated by sliding, and the twin deformation began to occur when the sliding became difficult. Misorientation played an important role on the crack behavior.

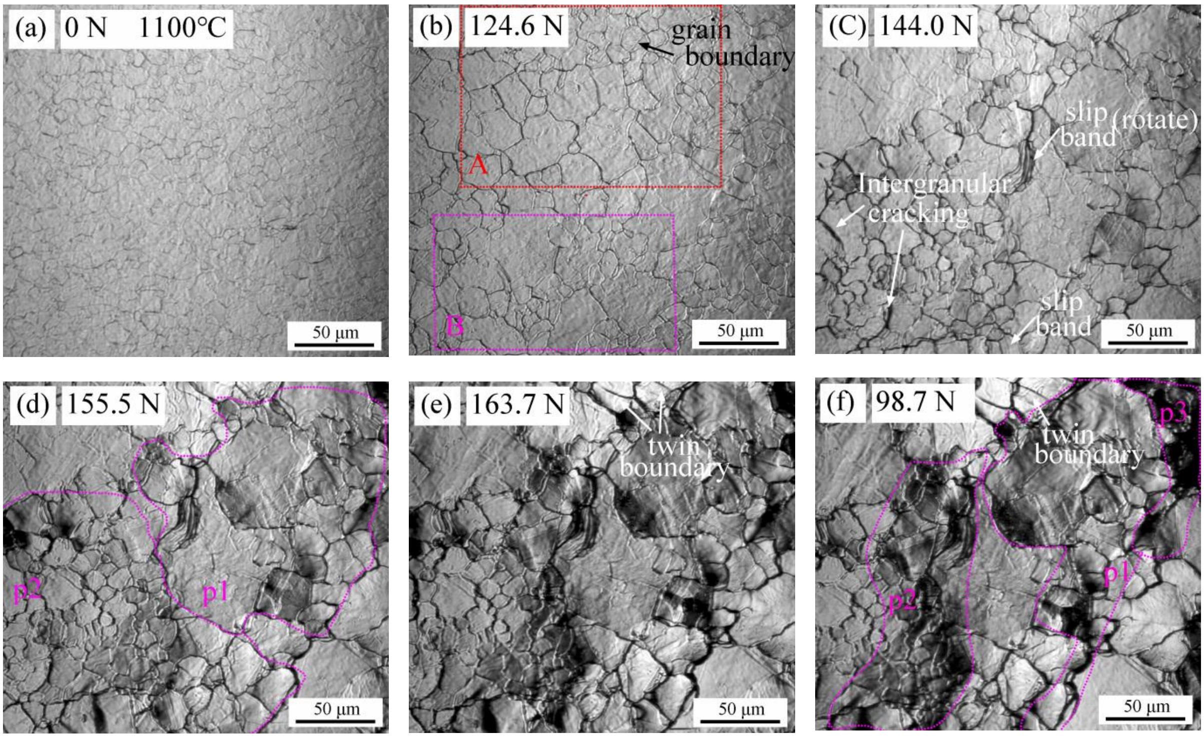

Figure 4. Deformation and crack evolution during in-situ tensile test (a) 0N (b) 124.6N (c) 144N (d) 155.5N (e) 163.7N (f) 98.7N.

When the sample surface was corroded by 4% Nital solution, the surface topography in the SEM field can be used for DIC analysis. It could be found that cracks were mainly initiated and propagated in the position with a large plastic strain. The strain concentration showed a significant effect on crack initiation.

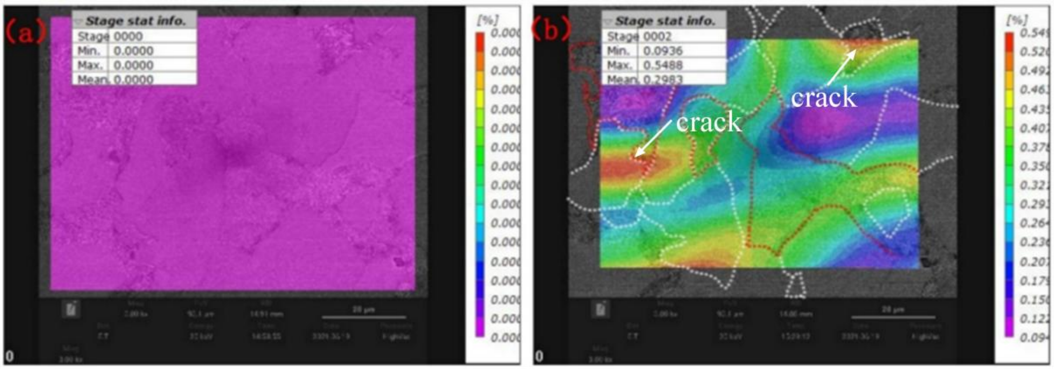

Figure 5. (a)DIC test datum (b)the DIC strain distribution.

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4. Conclusion

Based on the in-situ high-temperature SEM and laser scanning confocal microscope (LSCM), the high-temperature plastic deformation and failure behavior of X65 pipeline steel at 1000 ℃ and 1200 ℃ were studied in this paper, and the strain evolution behavior in this process was analyzed by DIC technology. The main conclusions were drawn as follows:

(1) When the temperature rose to 753.3 ℃, austenization appeared, and the grain boundary was relatively obvious. When the temperature rose to 932.2 ℃, a large amount of carbide began to precipitate near the original austenite boundary, and when the temperature continued to rise to 1000.2℃, the precipitated carbide began to redissolve.

(2) The external load showed a great effect on the growth of the grains, and the grains grew rapidly by swallowing each other. The grain size, material performance, and misorientation played an important role during the deformation and crack evolution.

(3) At high temperature, cracks were mainly initiated and propagated in the position with a large plastic strain. The strain concentration showed a significant effect on crack initiation.

Acknowledgments

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