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Fatigue Behavior Investigation and Micro-Analysis of X80 High-Strain Line-pipe

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Abstract Symmetrical push-pull low circle fatigue tests were carried out with conventional and high-strain X80 linepipe material respectively. Micro-analysis was performed for deformation mechanism as well. Results showed that high-strain X80 linepipe material exhibited a lower cyclic softening rate and a longer low-circle fatigue life than those of conventional X80 linepipe material. Cyclic response curves showed that the cyclic softening occurred at all strains amplitude (0.4%~1.4%) on two X80 line pipe materials. For conventional X80 linepipe material, cyclic softening was found after slight cyclic stress saturation at high strain amplitude of 1.0% ~1.4%. however, for high-strain X80 linepipe material, cyclic softening was observed after slight cyclic hardening at high strain amplitude of 1.0% ~1.4%. Fractography analysis suggested that transgranular fracture with well-developed fatigue striations and obvious second crack is the predominant failure mode. The amount of second crack was fewer detected in high-strain X80 linepipe material than that in conventional X80 linepipe material. TEM examination reveals that the primary deformation mode of two kinds of material was dislocation slipping. Abundant dislocation glide bands and dislocation cells were formed at grain boundary as strain amplitude increased. The number of dislocation blocked and wall thickness of dislocation cells in conventional X80 linepipe material are much greater than that in high-strain X80 linepipe material. The better cyclic deformation resistance of high-strain X80 linepipe material was ascribed to relative more M/A islands distributed inside the grains or grain boundaries.

Keywords High-strain line pipe; Low-circle fatigue; Strain amplitude; Dislocation; M/A

1. Introduction

Fatigue is a common failure mode of oil & gas pipeline. Fatigue fracture of pipeline is mainly caused by various alternating stress, which derives from pressure oscillation, layering of gas medium and all sorts of external variable load, such as vibration led by vehicle on the buried pipeline, fluvial abrasion of river, quicksand migration in desert and waves wash in offshore pipeline [1, 2]. Alternating stress can lead to local and alternative plastic deformation where stress concentration occurs, then fatigue failure of pipeline. In addition, since a lot of long distance, high pressure and large throughput pipeline set up in the harsh geological area, such as landslide, permafrost and seismic, buckling always caused by serious local plastic deformation of pipeline by bending, axial compression and axial tension stress. However, fracture can not be accomplished only once, low circle fatigue always becomes the final reason for the fracture of pipeline [3, 4]. Therefore, investigation on fatigue behavior of pipeline, especially low circle fatigue behavior is very significant for providing the theoretical suggestion for design, material selection and lifetime prediction of pipeline operating in the harsh condition. In this paper, the difference of low-circle fatigue performance between two X80 linepipe materials has been discovered by sub-structure evolution observation as well.

2. Experimental

The material of X80 conventional and high-strain line pipe used in this paper is obtained by TMCP and UOE forming technology. The microstructure of both X80 linepipe material mainly consists of granular bainite, polygonal ferrite and M/A as show in figure 1. While comparing the detailed feature of conventional and high-strain X80 linepipe material, some differences can be detected that the grain size of first one is much finer and the content of polygonal ferrite and M/A of second one is much higher. The tensile properties of both X80 pipe are listed in table 1. It can be found that the tensile strength, ductility and strain hardening property of X80 high-strain pipe are much better than conventional pipe.

Since cyclic load that leads to fatigue failure always derives from axial stress, such as bending, compression and tension stress, round bar specimen with uniform section is cut from the pipe body along the longitudinal direction where is adjacent to the weld seam with 90° and machined with a gauge length of 12.5mm as shown in figure 2. Low circle fatigue test has been conducted on electro hydraulic servo fatigue testing machine Instron 1341 in terms of GB/T 15248-2008, in which tension-compression symmetric cycle and total axial strain control has been used. Triangle wave loading is adopted in tests to ensure a stable strain rate during the process of cyclic tension and compression and an obvious inflection point of sluggish loop. Strain amplitude of tests are 0.4%, 0.6%, 0.8%, 1.0%, 1.2% and 1.4%, strain rate used in tests is 4×10^{-3}mm/s, and strain ratio is -1.

Fatigue fracture has been investigated on SEM JSE-6700F. Specimen for TEM investigation was cut from the specimen in the range of gauge length along section direction after fatigue tests with EDM and machined by mechanical thinning and electrode polishing. Deformation microstructure observation has been carried out on the TEM JEM-200CX using an accelerating voltage as 200Kv.

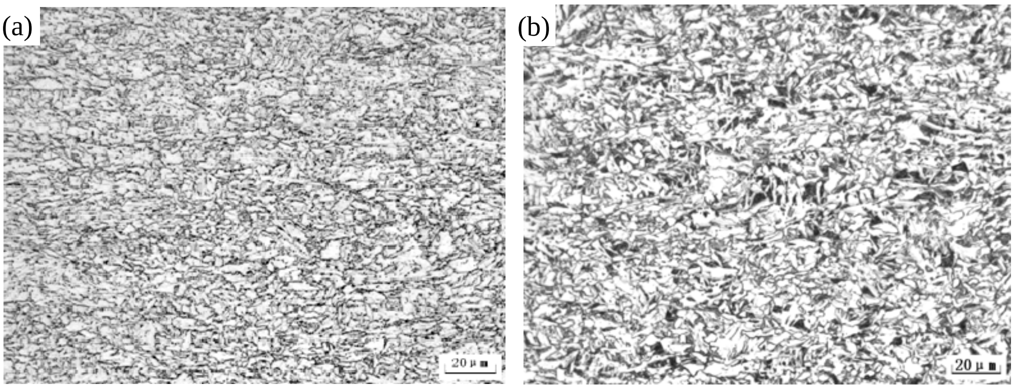

Figure 1. Micro-structure of X80 linepipe: a) conventional, b) high-strain

Table 1. longitudinal tensle property of X80 linepipe (round bar, gaugh length 50mm, diameter 12.7mm)

No.	σ_s/MPa	σ_b/MPa	δ/%	σ_s/σ_b	*UEL*/%	*n*
Conventional	580	653	24.1	0.89	7.25	0.0688
High-strain	569	729	24.3	0.78	7.87	0.1126

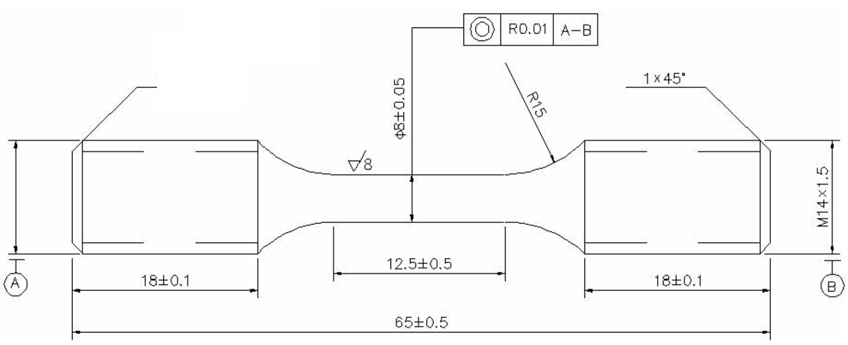

Figure 2. Specimen of low circle fatigue test

3. RESULTS

3.1. Cyclic stress response behavior

The relationship between stress amplitude and lifetime of two X80 linepipe steel material has been investigated with different strain amplitude 0.4%~1.4% as shown in figure 3. Comparing figure 3 (a) and (b), some common cyclic fatigue characteristics of X80 linepipe material suffered with different strain amplitude can be concluded: i. the stress amplitude of two X80 linepipe materials declines with the increment of cyclic time Nf, which means that material shows a general cyclic softening during the process of cyclic deformation with different strain amplitude. ii. softening rate is relative lower when material suffers with low strain amplitude 0.4%~0.8%, softening rate greatly increases as strain amplitude exceeds 0.8%, total softening rate of material shows an incremental tendency as strain amplitude increased. iii. cyclic fatigue lifetime is gradually shortened as strain amplitude increases. According to figure3, some different cyclic deformation feature also can be found: i. in the earlier phase of cyclic deformation, e.g. Nf lower than 4, two X80 linepipe material shows an obvious cyclic softening feature when materials suffer with lower strain amplitude 0.4%~0.8. However, as strain amplitude exceeds 0.8%, X80 conventional linepipe material shows a cyclic saturation feature, while X80 high-strain linepipe material presents a cyclic hardening behavior in which hardening level is prompted as stress amplitude increased. ii. the softening rate of X80 high-strain linepipe material is much higher than X80 conventional linepipe during the whole process of cyclic deformation with different strain amplitude. iii. under the same strain amplitude, cyclic stress amplitude of X80 high-strain linepipe material is always higher than X80 conventional linepipe material, which maybe ascribes to the much higher strength of X80 high-strain linepipe material.

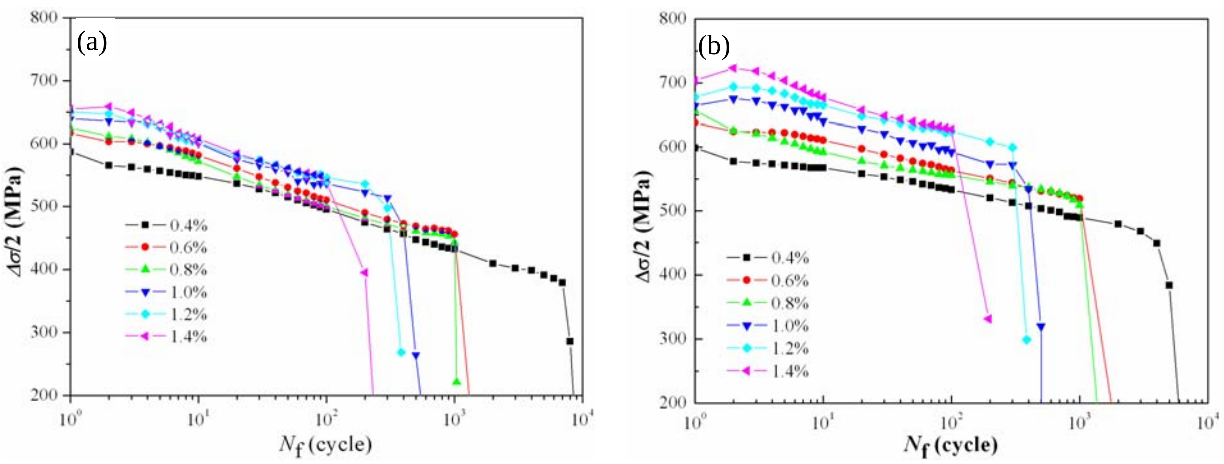

Figure 3. Relationship between stress amplitude and lifetime of X80 linepipe: (a) conventional, (b) high-strain

3.2. Cyclic stress strain behavior

Cyclic strain resistance in steady state of metallic material always can be indicated by cyclic stress strain curve. When comparing it with static tension curve, the feature of cyclic strain behavior can be found. In terms of relationship between $\Delta\sigma/2$ and $\Delta\varepsilon_p/2$, cyclic stress strain curve can be obtained after test data linear fitted in the logarithmic coordinates by least square method. Static tension curve and cyclic stress strain curve of two X80 linepipe material is shown in figure 4. It is found that two materials present cyclic softening characteristic in the range of strain amplitude. Softening level is much stronger under lower strain amplitude, while, softening level decreases with the increment of strain amplitude. It can be observed that cyclic hardening rate of two X80 linepipe material is higher than that of static tension. It means that although the material apparently presents cyclic softening, since uniform distribution ability of deformation elevated by hardening, cyclic level is declined with the increment of strain amplitude [5].

Cyclic stress strain curve of two X80 linepipe material has been compared as figure 5 shown, it displays that cyclic softening level of X80 high-strain linepipe material is much lower than X80 conventional linepipe material under the same strain amplitude and the difference of stress amplitude between them gradually enhances as strain amplitude increases, which implies that X80 high-strain linepipe material has a much better cyclic strain resistance.

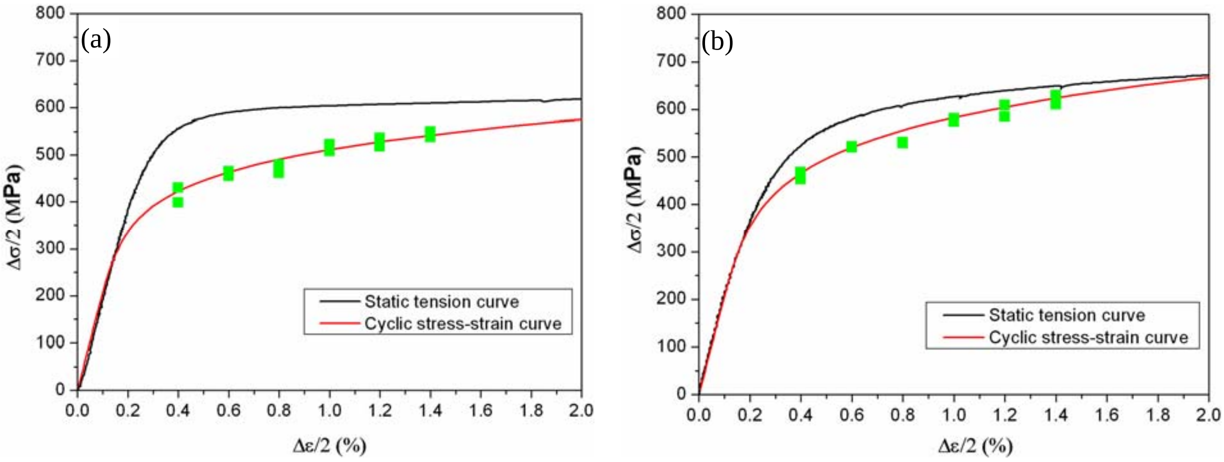

Figure 4. Cyclic strain stress curve and static tension curve of X80 linepipe material: (a) conventional, (b) high-stain

3.3. Fatigue lifetime

According to Manson-coffion equation, the relationship between strain and lifetime of X80 conventional and high strain linepipe material can be extrapolated as equation (1) and (2) after test data linear fitted in the logarithmic coordinates by least square method.

$$\frac{\Delta\varepsilon_t}{2}=\frac{\Delta\varepsilon_e}{2}+\frac{\Delta\varepsilon_p}{2}=0.0044(2N_f)^{-0.0677}+0.3171(2N_f)^{-0.5572} \quad \text{(conventional)} \qquad (1)$$

$$\frac{\Delta\varepsilon_t}{2}=\frac{\Delta\varepsilon_e}{2}+\frac{\Delta\varepsilon_p}{2}=0.0073(2N_f)^{-0.1158}+0.2159(2N_f)^{-0.5032} \quad \text{(High-stain)} \qquad (2)$$

Figure 6 shows the strain-lifetime curve of two X80 linepipe materials. It indicates that lifetime of X80 high-strain linepipe material is much higher than X80 conventional linepipe material when stain amplitude is much lower as 0.4%~1.0%. When strain amplitude exceeds 1.0%, the lifetime of two X80 linepipe materials almost has no difference. Generally, the lifetime of X80 high-strain linepipe material is much higher than X80 conventional linepipe material.

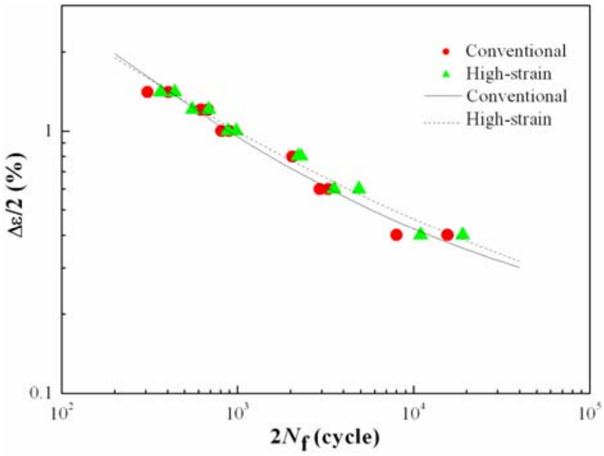

Figure 6. Strain-lifetime curve of X80 linepipe material

3.4. Fractography analysis

Fracture of low-circle fatigue specimens of two X80 linepipe material has been investigated by SEM. Figure 7 shows the facture appearance of specimen suffered with 1.2% strain amplitude. It is observed that fatigue fracture consists of 3 zones, including fatigue crack initiation, propagation and final fracture. Fatigue crack always initiates at surface and propagates along the direction perpendicular to the normal tensile stress (axial of specimen). The excircle edge of fracture fully distributes with fatigue steps presented with a radial pattern, and the amount of fatigue step increases with the increment of strain amplitude, which implies that the quantity of fatigue source increases accordingly. Comparing figure 7 (a) and (b), it can be found that the amount of fatigue step and radial stripe of X80 conventional linepipe material is much more than X80 high-strain linepipe material. Since fatigue specimen suffered tension-compression load, the zone adjacent to crack initiation presents obvious trail of extruding and grinding which resulted by the mutual extruding and rubbing between upper and lower surface of crack when fatigue crack stretched and closed repeatedly. Extruding and grinding become much heavier with the increment of strain amplitude and load applied on material, which makes the zone near the crack initiation much smoother as shown in figure 8. It also indicates that in initiation zone of X80 high strain linepipe material has a much smoother feature than X80 conventional linepipe material and its step is also much lower, which implies that high-strain linepipe material has a relative lower crack initiation rate.

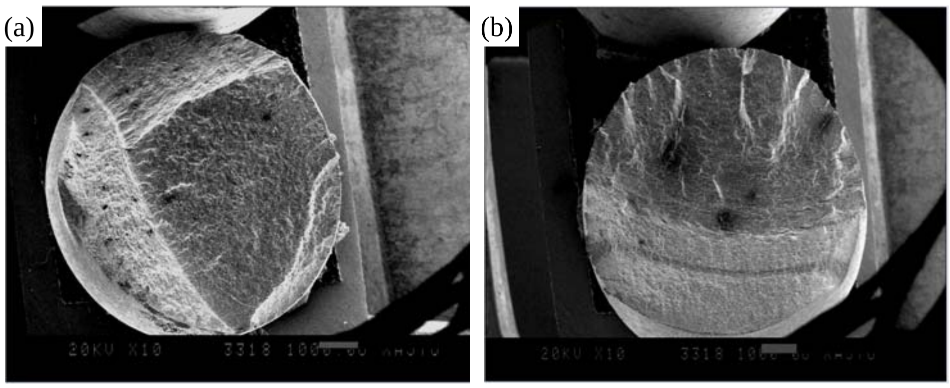

Figure 7. Macro-appearance of low-circle fatigue fracture of X80 linepipe material ($\Delta\varepsilon / 2$ =1.2%): (a) conventional, (b) high-strain

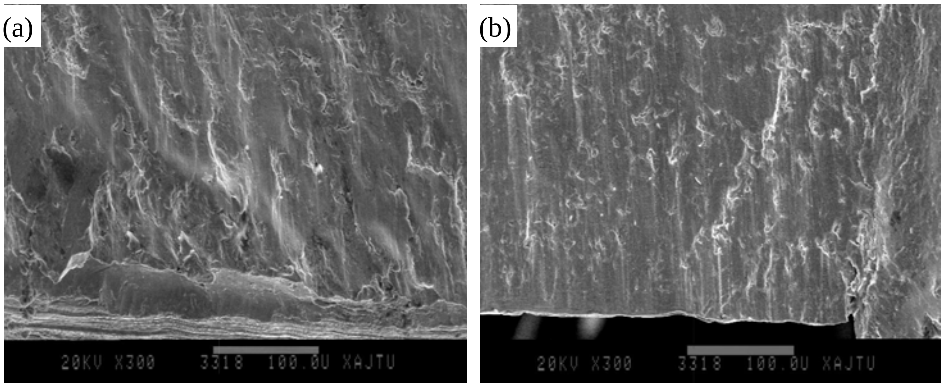

Figure 8. Micro mophology of fitigue crack intiation zone of X80 high-strain linepipe material ($\Delta\varepsilon/2$ =1.2%)

Micro-morphology of fatigue crack propagation zone of X80 linepipe material under the condition of different strain amplitude is shown in figure 9 and figure 10. It is found that the typical characteristic of propagation zone of specimen is fatigue striations and second crack which induced by cyclic load with the strain amplitude of 0.4%, as shown in figure 9. Comparing with figure 9 (a) and figure 9 (b), it can be found that the amount of second crack and the spacing of fatigue striation of X80 conventional linepipe material is much higher than X80 high-strain linepipe material, which means that fatigue crack propagation rate of X80 conventional linepipe material is much higher.

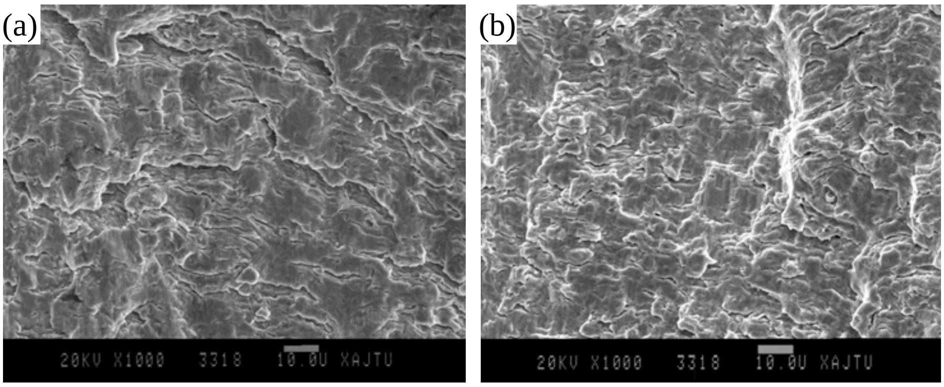

Figure 9. Micro mophology of fitigue crack propagation zone of X80 high-strain linepipe material ($\Delta\sigma/2$ =0.4%): (a) conventional，(b) high-stain

When strain amplitude increases to 1.2%, much more second cracks appear since load enhanced. Since the heavy extruding and grinding of fracture surface, propagation zone turns to be much smoother, tire-shaped pattern presents and fatigue striations almost disappears as shown in figure 10. The emergence of tire-shaped pattern means that fatigue crack speed dramatically increases under the condition of high strain amplitude which can enormously shorten the fatigue lifetime of material [6]. According to figure 10, X80 high-strain linepipe material presents a much obvious tire-shaped patter in crack propagation zone which presents a typical brittle fatigue feature.

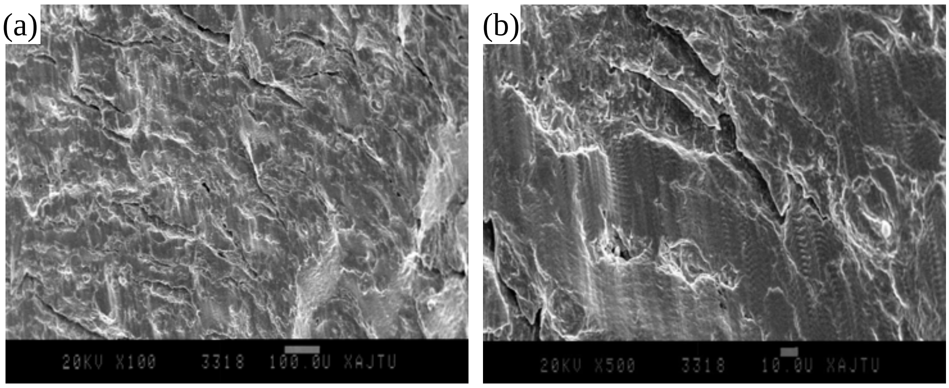

Figure 10. Micro mophology of fitigue crack propagation zone of X80 linepipe material ($\Delta\sigma/2$ =0.4%): (a) conventional，(b) high-stain

4. Sub-structure observation and Discussion

Low-circle fatigue tests results of two X80 linepipe materials as presented above show that cyclic deformation behavior of both X80 linepipe materials is cyclic softening. In addition, the softening rate of X80 high-strain linepipe material is much lower than that of X80 conventional linepipe material, the fatigue lifetime of X80 high-strain line pipe material is much longer as well. Generally, cyclic softening behavior always decides by the evolution of micro sub-structure of material suffered for cyclic loads. Usually, possible reasons for cyclic softening are reduction of dislocation density resulted by opposite screw dislocation meetion and counteraction, dislocation realignment and formation of sub-grain or dislocation cell, decline of friction stress induced by dislocation off-pining which original pinned by solute atoms. Therefore, some investigations on both X80 linepipe materials after cyclic deformed have to be performed to discover the different cyclic strain behavior of both X80 linepipe materials.

Since ferrite is relatively soft and has much fewer precipitated carbide, plastic deformation always preferentially happens inside it. Therefore, dislocation motion in ferrite can reflect the substructure evolution of material. Figure 11 presents substructure morphology of two ruptured X80 linepipe materials which suffered with lower cyclic strain amplitude 0.4%. X80 conventional linepipe material has a much heavier density of dislocation inside ferrite, and an incomplete dislocation cell is has formed by tangled dislocation as shown in figure 11 (a). However, it can be observed from figure 11 (b) that dislocation in ferrite and bainite is fairly higher and abundantly tangled on the grain boundary, while dislocation cell has not formed yet. The presence of dislocation of X80 high-strain linepipe material mainly is outcrop and dislocation line in ferrite due to much higher density of M/A constituent that can improve the deformation coordinate capability of material and postpone the occurrence of dislocation cell in ferrite. The difference of dislocation configuration between two materials results in the lower cyclic softening rate of X80 high-strain linepipe.

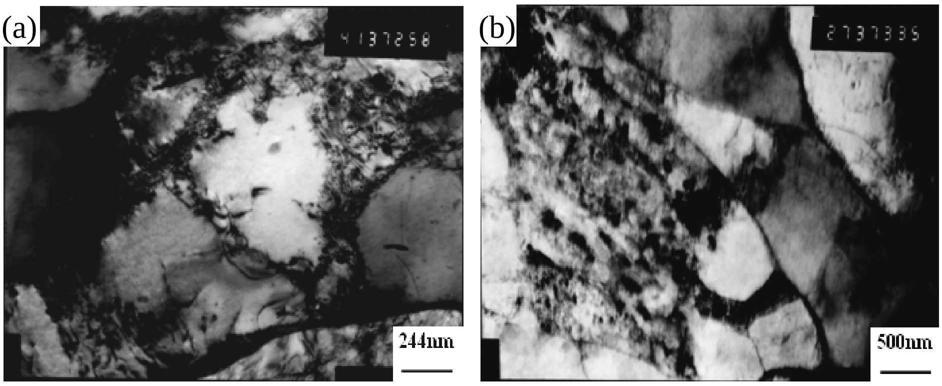

Figure 11 Substructure morphology of X80 linepipe material by 0.4% strain amplitude: (a) conventional (*Nf* =7800), (b) high-strain (*Nf* =9500)

Figure 12 (a) ~ (b) shows the dislocation configuration of X80 conventional linepipe material. With the increment of strain amplitude up to 0.8%, dislocation density in ferrite of X80 conventional linepipe material further decreases, single dislocation line almost disappears and complete dislocation has been formed as figure 12 (a) shown. Dislocation in M/A island begins to be polygonzaition and dislocation cell is going to be formed, in the same time, the amount of dislocation which bypasses second particles and accumulates around increases as shown in figure 12 (b) which results the realignment of dislocation. The formation of dislocation cell and declines of dislocation density causes the cyclic softening rate increase of material under 0.8% strain amplitude. Figure 12 (c) ~ (d) shows the dislocation configuration of X80 high-strain linepipe material. An obvious variation of dislocation configuration happens in X80 high-strain line pipe material with the increment of strain amplitude. Dislocation cell with relative thinner wall has started to be formed in ferrite in some area, which implies that with the occurrence of cellular structure, cyclic softening rate of X80 high-strain line pipe material suffered 0.8% strain amplitude is significantly improved comparing with 0.4% strain amplitude. Furthermore, it also can be observed that the tendency of dislocation cellular structure formation is much more obvious in ferrite surrounded by M/A as shown in figure 12 (c). While, the dislocation configuration in ferrite not surrounded by M/A is dislocation line or tangled dislocation as show in 12 (d). The reason for this phenomenon is that deformation inside material focuses primarily on coordinating deformation among structures. That is to say, deformation firstly happens on ferrite with a lower strength which can induce dislocation annihilation or formation of dislocation cell after dislocation movement and occurrence of ferrite softening [7]. Meanwhile, since deformation of ferrite is restrained by plenty of M/A constituent, once ferrite has been deformed to a certain level, deformation on M/A island begins. Furthermore, since much more ferrite exits in X80 high-strain linepipe material, the resource for dislocation movement is much more than X80 conventional linepipe material. Therefore, deformation in ferrite is further suppressed and the formation of dislocation cell in ferrite is accordingly delayed, which results in the reduction of softening rate of ferrite. Perhaps, that is certain reasons for inducing of much lower softening rate of X80 high-strain line pipe material [8].

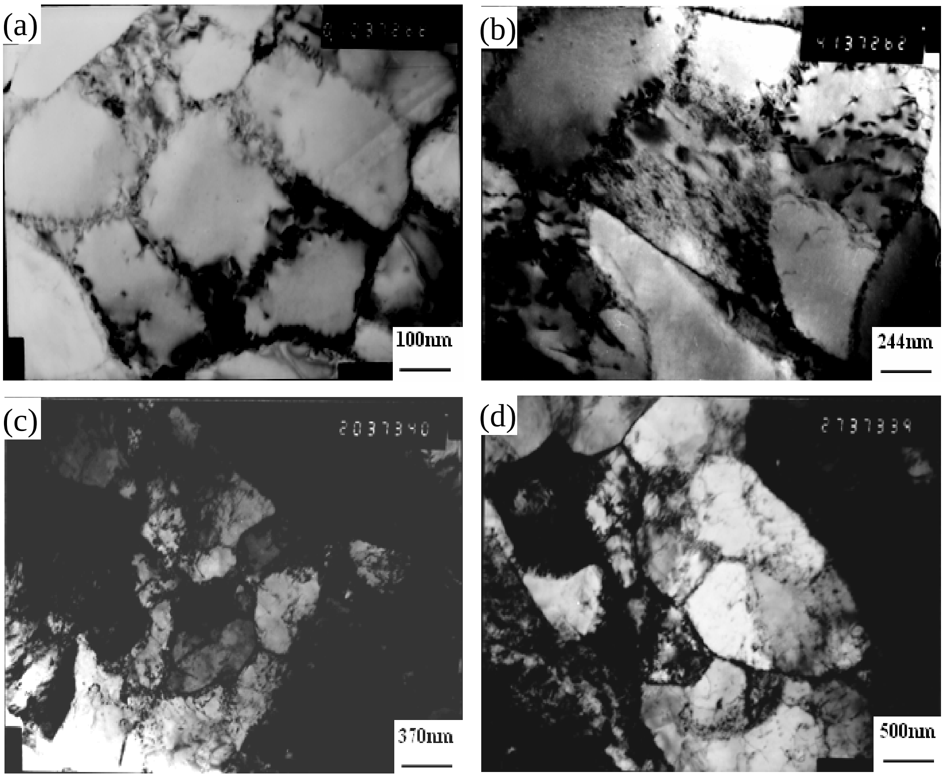

Figure 12. Substructure morphology of X80 linepipe material by 0.8% strain amplitude: (a)~(b) conventional (*Nf* =1027), (c)~(d) high-strain (*Nf* =1145)

Figure 13 presents the substructure morphology of two X80 linepipe material suffered 1.2% strain amplitude. For X80 conventional linepipe material, dislocation cell has been rapidly formed and cell wall-thickness obviously increases due to the dislocation pilling up nearby as indicted by figure 13(a). It is observed in figure 13 (b) that dislocation cell has been formed in ferrite surrounded by M/A, which further demonstrated the decrease of softening rate resulted by M/A that can obstruct deformation and postpone the development of dislocation cell in ferrite of X80 high-strain linepipe material.

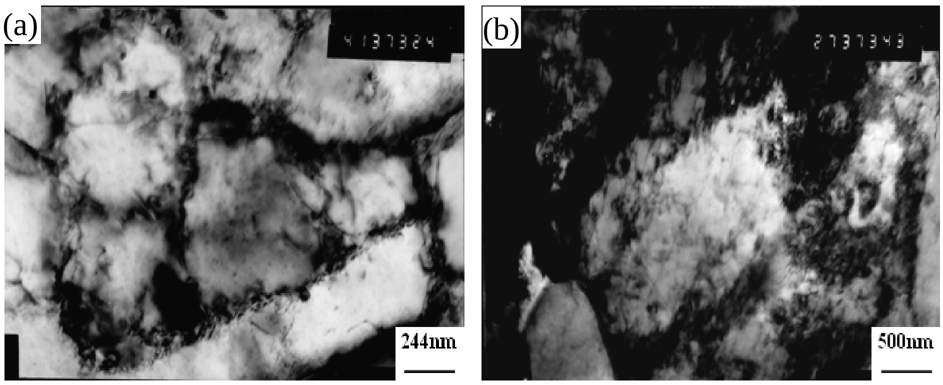

Figure 13. Substructure morphology of X80 linepipe material by 1.2% strain amplitude: (a) conventional (*Nf* =340), (b) high-strain (*Nf* =343)

5. Conclusion

Generally, two X80 linepipe materials exhibit a cyclic softening behavior under the cyclic load. Softening rate of two X80 linepipe materials show an incremental tendency as strain amplitude increased. Cyclic fatigue lifetime of two X80 linepipe materials is gradually shortened as strain amplitude increases. In the earlier phase of cyclic deformation with strain amplitude exceeding 0.8%, X80 conventional linepipe material shows a cyclic saturation feature, while X80 high-strain linepipe material presents a cyclic hardening behavior. The softening rate of X80 high-strain linepipe material is much higher than X80 conventional linepipe during the whole process of cyclic deformation. Under the same strain amplitude, cyclic stress amplitude of X80 high-strain linepipe material is always higher than X80 conventional linepipe material, which maybe ascribes to the much higher strength of X80 high-strain linepipe material.

Cyclic softening level of X80 high-strain linepipe material is much lower than X80 conventional linepipe material under the same strain amplitude and the difference of stress amplitude between them gradually enhances as strain amplitude increases, which implies that X80 high-strain linepipe material has a much better cyclic strain resistance. The fatigue lifetime of X80 high-strain linepipe material is much higher than X80 conventional linepipe material.

In initiation zone of X80 high strain linepipe material has a much smoother feature than X80 conventional linepipe material and its step is also much lower, which implies that high-strain linepipe material has a relative lower crack initiation rate. the amount of second crack and the spacing of fatigue striation of X80 conventional linepipe material is much higher than X80 high-strain linepipe material, which means that fatigue crack propagation rate of X80 conventional linepipe material is much higher. X80 high-strain linepipe material presents a much obvious tire-shaped patter in crack propagation zone which presents a typical brittle fatigue feature.

Substructure evolution investigation reveals that the primary deformation mode of two X80 linepipe material is islocation slipping. As strain amplitude increased, dislocation cell developed gradually from dislocation line and tangled dislocation in two X80 linepipe materials. Dislocation density in X80 high strain linepipe material is much higher than X80 conventional linepipe material under various strain amplitude. The formation of dislocation cell or dislocation realignment of X80 high-strain linepipe material is always later than X80 conventional linepipe material. Ferrite deformation has been restrained in X80 high-strain linepipe material due to the higher amount of M/A and ferrite which postponed the formation and development of dislocation cell and caused a much lower softening rate.

Acknowledgements

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