

Microstructure evolution of grade X100 Pipeline under plastic deformation condition

LIHUA QI^{a,b*}, JING NIU^{a,b}, LONG YANG^a, YAORONG FENG^a, JIANXUN ZHANG^b

^aTubular Goods Research Center of CNPC, China

^bSchools of Material Science and Technology, Xi'an Jiao Tong University, China

The effects of plastic deformation on the microstructure evolution of grade X100 pipeline were investigated by SEM, TEM and EBSD test. The result showed that quasi-polygon ferrite deformed firstly under tension stress function, subsequently, both ferrite and granular bainite change remarkably with the value of plastic strain increase. Furthermore, the microscopic orientation concentrates in $\{110\}$ <111> direction before the deformation, while crystal orientation in $\{110\}$ and $\{112\}$ direction enhanced after the deformation. Due to M/A island on the acicular ferrite and the bainite boundary nails the dislocation, it causes the distortion not to be suitable occurs. Under the tension stress function, the inclusion becomes the micro-crack nuclear core, and increases along with the plastic deformation expands, finally connects causes the crack penetration until the expiration.

(Received June 11, 2010; accepted July 14, 2010)

Keywords: X100 pipeline, Plastic deformation, Inclusion, M/A constitution

1. Introduction

Pipeline used for the transportation of crude oil or natural gas over a long distance. At present, requirement for natural gas maintains increasing rapidly at international. Recent researches indicated the significant advantages of using higher grade linepipes, such as X100 even X120 grade pipeline, in constructing long distance pipeline, because it can improve transportation efficiency of gas pipelines by increasing internal pressure, and material cost be saved correspondingly by reducing wall thickness of pipe body and consumable for girth welding [1-5]. First of all, Due to complicated lay circumstance of linepipes and multiple-region of earthquake and geology casualty, gas pipelines will bear rather large displacement and stress. Secondly, It is reported that the crosswise strain rate of UOE pipeline achieves 2% in the manufacture process, and the maximum flexure deformation at part of the pipeline achieve 4%~5% when it lay through multiple-region of earthquake and geology casualty [6-10]. Thirdly, there are lots of natural gas let out or exploration accident due to pipeline plastic fracture in the world. Therefore, in order to guarantee property stability and operational safety of the pipeline, it is necessary to research the microstructure evolution mechanism under plastic deformation condition. In this paper, the grade X100 pipeline microstructure and texture transformation were investigated during the in-situ plastic tensile process.

2. Experimental

Metallographic, SEM, EBSD and TEM experiments were prepared from the 1/4 thickness position of the pipelines steel, which ingredient (w%) are C 0.064, Si 0.095, Mn 1.69, Cr 0.013, Mo 0.031, Ni 0.2, Nb 0.042.

In-situ SEM specimens were prepared from 1/4 thickness position of the pipeline steel and processed 1.0mm thickness by linear cutting machine, as shown in Fig. 1. The specimen was polished and etched with 2% HNO₃+98% alcohol. The specimen was maintained on JSM-5800 stretcher to observe microstructure transformation, crack initiation and expansion through controlling load-on velocity. The TEM specimen was cut into 0.3mm thickness by linear cutting machine, and then reduced it below 50μm on MTP21A instrument and observed by H-800 TEM instrument.

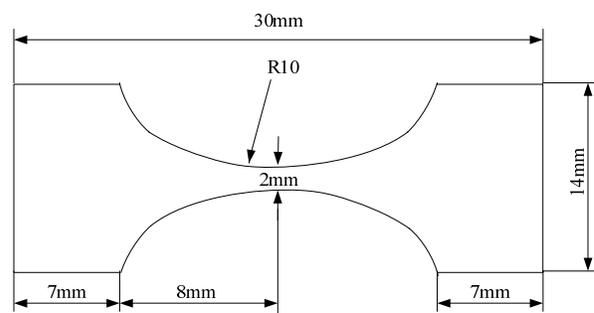


Fig. 1. Schematic picture of in-situ SEM specimens.

3. Results

3.1 Microstructure deformation

SEM picture, TEM picture and diffraction pattern of the grade X100 pipelines microstructure are shown in Fig.2. It is consisted of acicular ferrite, granular bainite,

M/A constituents (a mixture of martensite plus retained austenite) and little of quasi-polygon ferrite. The crystal grain sizes of the acicular ferrite and granular bainite are small. Lots of M/A constitutes laid uniformly in granular bainite boundary and on acicular ferrite boundary, which increase the yield strength and tensile strength of grade X100 pipelines. The acicular ferrite plank (length) the axial ratio distinction approximately is about 3:1. The morphology M/A constitute in granular bainite boundary is strip-shaped and the size is about 50nm, as shown in 1, 2 and 3 regions of Fig.2 (b). High density dislocation

assumes the tangle or the grid configuration. This kind of tangled or the existence node's dislocated grid configuration is advantageous to the dislocation stabilization and maintains high dislocation density, as in Fig.2 (b) [11]. Fig. 2(c) is the ferrite and M/A constitute diffraction pattern. According to the TEM picture of the microstructure, it is proved that the M/A constitute is mainly composed of high carbon martensite and some retained austenitic, but no twin martensite, which suggested that base structure has well toughness.

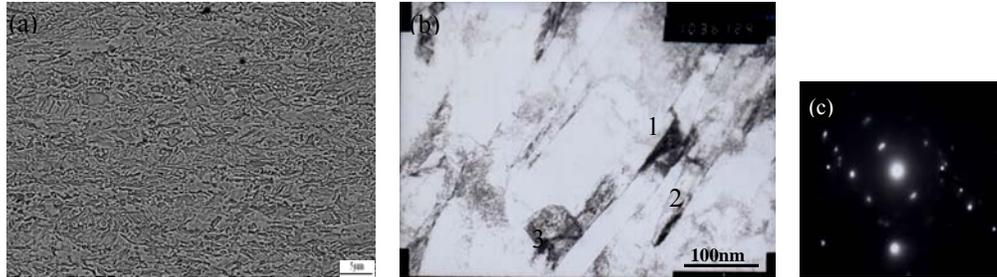


Fig. 2. SEM and TEM pictures of grade X100 pipelines of metallurgical structure and diffraction pattern of ferrite and M/A constitute.

When the tensile strain applied on the both ends of specimen, the microstructure morphology change at the surface of specimen can be studied with the strain increase. Slip deformation was observed primitively in the crystal grain of quasi-polygon ferrite, as shown in Fig. 3 A region. Subsequently, when the plastic deformation increases, big grain sizes of acicular ferrite and granular bainite slipped deformation gradually, as shown in Fig. 3 arrow 1, and the

deformation also emerged between the deformation bainite and the neighboring acicular ferrite crystal grain, as in Fig. 3 arrow 2. At the same time, bulges appear on the surface of the distortion granular bainite and the acicular ferrite. But there is not obvious distortion in the region of small granular bainite crystals gathered together, and maintains the original shape. It displays the good anti-plastic deformation ability, see Fig. 3 B region.

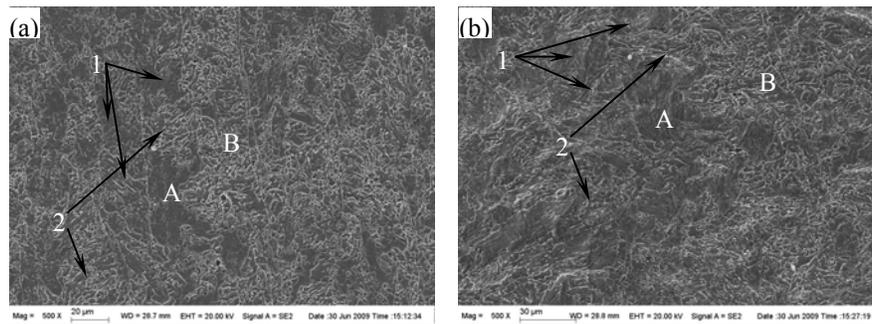


Fig. 3. SEM picture of polygon ferrite microstructure transformation (a) original (b) after tensile.

Fig. 4 is SEM picture of acicular ferrite microstructure transformation about original and after tensile. When the plastic deformation further increases, the tension stress still increased but the growth rate reduced gradually, both tiny acicular ferrite and the bainite crystal grain has been deformation. It is clear that the tension stress grown slowly with the plastic deformation increase, the big grain size of ferrite deformed in the first place. When the deformation further increases, coordinated deformation happened between the acicular ferrite and the granular bainite crystal grain, and the bugles raised on the surface of big size

deformation crystal, just like about mentions. The grain boundary of ferrite and bainite also has the bending deformation along with it, but the original austenite crystal boundary was still invariable, see Fig.4 (b) arrow 1. The distortion range of the small grain size of acicular ferrite and granular bainite is small, as shown in Fig.4 (b) A place. With stress further enlargement, the entire crystal grain surface presents bugles, and it can not distinguish basically out the original austenite crystal boundary, shown in Fig. 5 (a).

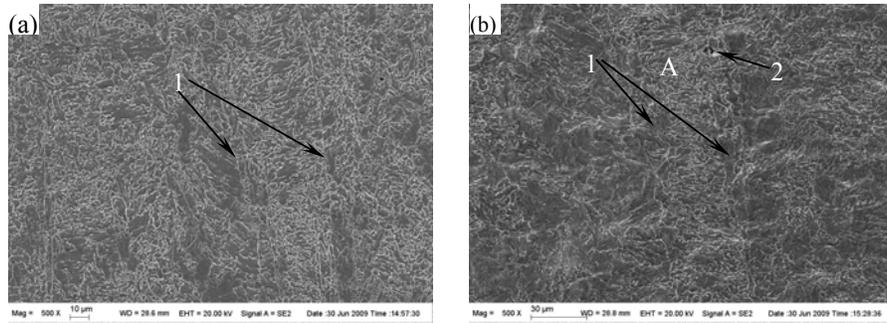


Fig. 4. SEM picture of acicular ferrite microstructure transformation (a) original, (b) after tensile.

3.2 Formation and expansion of micro-crack

Fig. 5 is the picture of micro-crack formation and expansion. During the stretches process, when the tension stress achieves the tensile strength, the tensile strength no longer increases, but the test specimen still has slow plastic deformation. Furthermore, the quasi-polygon ferrite has occurred distorts greatly, both the granular bainite and the acicular ferrite in the original austenite crystal interior deformed along the stretch direction. The original

austenite crystal boundary also has distortion. However, the oxide compound inclusion under the substrate surface is not easy to distort, therefore, where is easy to form the stress concentration. When the stress concentration attains some extent, the oxide compound mixture separated gradually with the substrate organization with tensile deformation's increase. It becomes the nucleus core of micro-crack, as in Fig. 5 (a) arrows 1 and 2, Fig. 4 (b) the arrow 2 and Fig. 5 (b) is the crack enlargement picture.

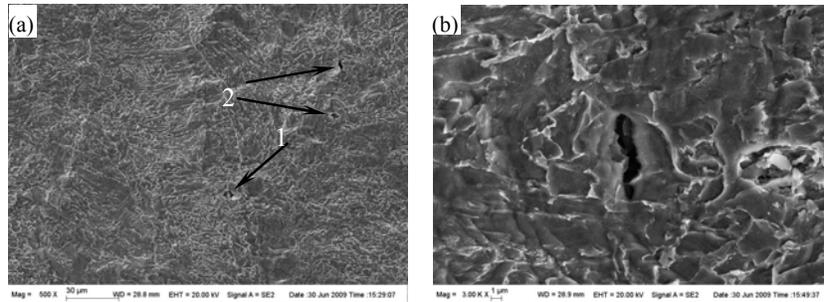


Fig. 5. Micro-crack formation during stretches process (a) and enlargement picture (b).

Along with deformation further increase, the micro-crack expanded rapidly, connected and formed the macroscopic transgranulation crack. Simultaneously, the tension stress rapidly reduces and the deformation speed suddenly increases, until test specimen breaks. Fig. 6 is the picture of the macroscopic crack formation and the enlargement picture. It can be observed that the inclusion

becomes the micro-crack nuclear core and the macroscopic fracture growth and the connection way, as shown in Fig. 6 the arrow 1 and 2. The facture morphology is dimpled fracture organization, and deep dimpled fracture distributes evenly. Thus it can be seen the toughness property of the grade X100 pipeline is very well under normal temperature condition.

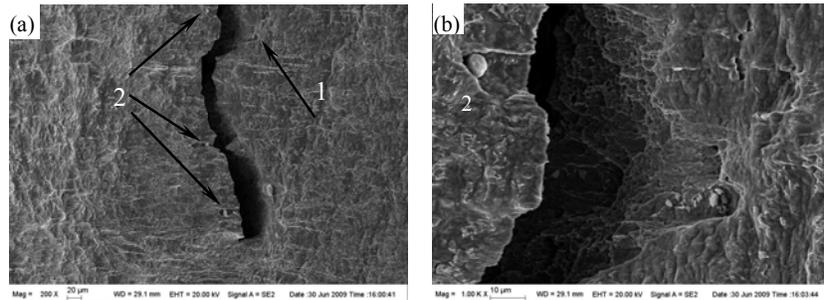


Fig. 6. Macro-crack formation and magnify picture after the stretches.

4. Analysis and discussion

According to the microstructure evolution of the pipe

body under the plastic deformation, it can be proved that the larger inclusion with no easy deformation caused the stress concentration and become the nucleus core of

micro-crack. Therefore, it is important to control the number and size of the inclusion of grade X100 pipeline or even higher grade pipeline. On the other hand, due to the M/A constitute possessed high intensity and no easy deformation, it may be the nucleus core of micro-crack. Therefore, of which morphology and distribution is important to the toughness and plastical deformation of the pipe body. There are two types morphology M/A constitute distributed in the microstructure of X100 pipeline: one type is fine M/A island distributed uniformly in the acicular ferrite and granular bainite base, another type is plate M/A constitute scattered mainly on crystal boundary, as shown in Fig. 2 (a).

In order to further observed the influence of the M/A constitute morphology on the formation and expansion of micro-crack, we made a tensile specimen with V-gap, as shown in Fig. 7.

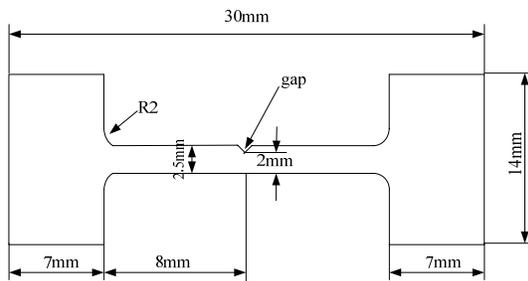


Fig. 7. Schematic picture of in-situ SEM specimens with V-gap.



Fig. 8. Micro-crack formation and cracks extension picture of in-situ SEM specimen.

Correspondingly, the microstructure transformation was investigated around the plastic deformation, it is shown in Fig. 9. Before the plastic deformation, the ferrite plank (see Fig. 3 (a)) is tiny and staggered mutually board strip constitute. The tiny M/A constitute distributed in the granular bainite, which can enhance substrate organization tensile and toughness. High density

When the strain reaches to tensile strength, micro-cracks emerge firstly on the boundary between M/A island and acicular ferrite, as shown in (a) and (b) place of Fig. 8. When load-strain maintain, the micro-crack at the surface between M/A island and acicular ferrite spread gradually, as shown in Fig. 8 arrow 1 and 2. On the one hand, the M/A particles enhanced the base strength of grade X100 pipelines, on the other hand, it can fix and fasten base structure, acicular ferrite and granular bainite, which can not easy to deform or slip. At the same time, there are some micro-cracks formed surrounding the already spread cracks to meet plastic yield. However, other base organize does not distort or present slip system. With the stress increase, the disfigurement at V-gap surface and cracks keep on spread and connect, as shown in arrows 3 and 4 of Fig.8. In the crack accumulation and the expansion process, other parts of test specimen substrate have not had the plastic deformation or present the slip bands, except for the micro crack formed around macroscopic cracks place between M/A island and the substrate phase boundary to adapt plastic deformation of the test specimen.

dislocation distributed in the ferrite plank internal, which assumes the tangle or the grid configuration. This kind of tangled or the existence node's dislocated grid configuration is advantageous to the dislocation stabilization and maintains high dislocation density [12-15]. The ferrite plank (length) the axial ratio distinction approximately is about 3:1.



Fig. 9. TEM pictures of grade X100 pipelines microstructure after plastic deformation.

After plastic deformation, the dislocation in ferrite plank distributed reticulated, which divided the entire ferrite plank into small regions, as shown in Fig. 9 (a). With plastic deformation increase, the dislocated grid formed gradually sub-grain boundary in the plank, in arrow 1 of Fig. 9 (b). Simultaneously, due to the M/A constitute possessed high strength and not easily deformation, the high intensity dislocation formed during

the deformation process gathers easily at its periphery and creates stress concentration, it forms the sub-grain boundary and the crystal boundary gradually, see Fig. 9(b) arrow 2. Even in certain defective areas especially inclusion area, the dislocation intertwines to cause the stress concentration, becomes the micro crack nucleating center, in Fig. 9(c) the arrow place.

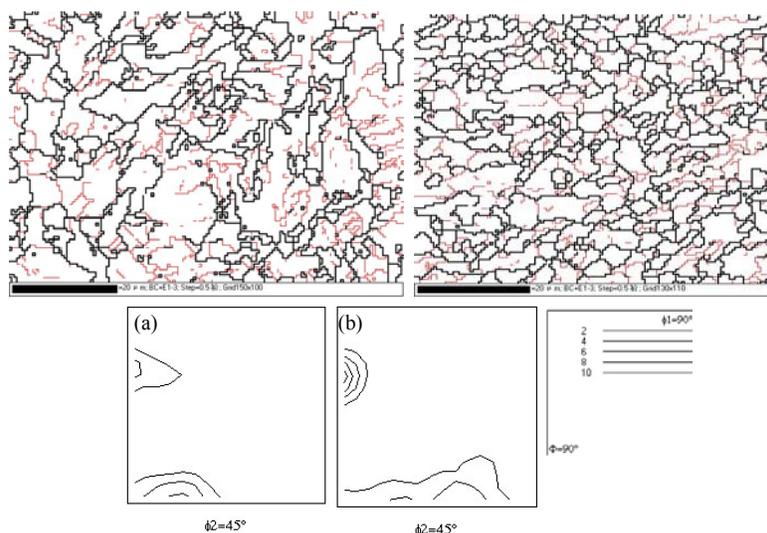


Fig. 10. Microstructure orientation and Texture component picture (a) original, (b) 5% tensile strain.

Fig. 10 is microscopic orientation and the corresponding ODF picture under original and after the tensile strain. The grain size (grain orientation angle is bigger than 15° , black streak in chart) is about $20\mu\text{m}$ before the tensile strain, and the massive mosaic structures distributed in the crystal grain interior (see red streak in chart). The sub-grain size approximately is $5\sim 6\mu\text{m}$. After tensile deformation, the grain size, about $5\sim 10\mu\text{m}$, reduces obviously. Some sub-grain boundaries in the crystal grain formed the new crystal boundary gradually under tension stress's function. Obviously, the tensile strain causes the crystal grain deformation and sub-grain boundary forms the new crystal boundary during the stretch process. Before the stretch, the crystal orientation is quite centralized, mainly concentrates in the $\{110\} \langle 111 \rangle$ orientation, the orientation density approximately is 6, $\{112\} \langle 111 \rangle$ direction has the weak texture orientation. After the stretch, the orientation density of $\{110\} \langle 111 \rangle$ reduces, but which expands along the entire $\{110\}$

orientation range. The orientation density of $\{112\} \langle 111 \rangle$ enhances and achieves above 8 [16-18].

4. Conclusions

For the microstructure deformation characteristic under in-situ tensile condition, it can be observed that quasi polygon ferrite with low yield strength deformed firstly. With plastic deformation increases, dislocation density in the bainite and the acicular ferrite crystal grain interior increases, it formed the slip bands gradually in the crystal grain interior and coordination deformed along tension stress direction. Due to accumulation of the slip bands and the dislocation on grain boundary, stress concentration on the bainite boundary increases correspondingly. It provides the energy of coordinate deformation for its crystal grain internal slip system. Furthermore, there exists stress concentration between no

deformation band and deformation area, when stress concentration attains certain extent, the inclusion or M/A constitute in two region boundary becomes micro-crack nuclear core. When the plastic deformation increases, the micro-crack rapidly expended and connected the macro-crack, until penetrated fracture. Before the deformation, the microscopic orientation concentrates in $\{110\}$ $\langle 111 \rangle$ direction, after the deformation, crystal orientation in $\{110\}$ and $\{112\}$ direction enhanced. For X100 level pipeline steel, the substrate organization is mainly composed of the acicular ferrite and the granular bainite, and the grain size is small (crystal grain size 12 levels). It is not easy to have the deformation. Under the tension stress function, the stress concentration around the inclusion is higher than that of other grade pipeline steel, therefore, the size, quantity and distributed situation of the inclusion and M/A constitute are very important to the body organization plastic deformation ability.

Acknowledgements

This work was supported by the National Postdoctoral Science Foundation of China (No. 18420006)

References

- [1] Li Helin. *Welded Pipe* **27**(6), 1211 (2004).
- [2] H. Takuya, T. Eiji, M. Hiroshi, A. Hitoshi, X100/X120 level high performance pipeline steel international high-level forum, 136 (2007).
- [3] V. Schwinn, S. Zajac, P. Fluess, K-H Tacke, X100/X120 level high performance pipeline steel international high-level forum, 251.
- [4] Chao Change, *Welded Pipe* **22**(2), 53 (1999).
- [5] P. C. M. Rodrigues, E. V. Pereloma, D. B. Santoc, *Material s Science and Engineering* **283A**, 136 (2000).
- [6] M. Okatsu, N. Ishikawa, S. Endo, N. Suzuki, 24th International Conference on Offshore Mechanics and Arctic Engineering, OMAE2005, Greece.
- [7] Wang Lubing, Ren Yi, Zhang Pengcheng, Wu Huibin. *Steel&Iorn* **43**, 80 (2004).
- [8] S. Okaguchi, M. Hamada, H. Makino, A. Yamamoto et.al. , X100/X120 level high performance pipeline steel international high-level forum, 158.
- [9] H.-G. Hillenbrand, A. Liessem, K. Biermann, S. M. Forschung et.al., X100/X120 level high performance pipeline steel international high-level forum, 189.
- [10] Y. Terada, Y. Shinohara, T. Hara, E. Tsuru et.al., X100/X120 level high performance pipeline steel international high-level forum, 333.
- [11] M. C. Zhao, F. R. Xiao, Y. Y. Shan, Y. H. Li et.al., *Acta Metallurgica Sinica* **38**(3), 283 (2002).
- [12] A. Glover et al. 22nd Int. Conf. OMAE. Cancun, Mexico, June 2003, ASME, OMAE2003-37429, 121.
- [13] H. Byounchul, G. K. Yang, L. Sunghak, M. K. Young et. al., *Metallurgical and Materials Transactions A*, **36A**, 2005 (2005).
- [14] H. Byounchul, M. K. Young, L. Sunghak, J. K. Nack et. al., *Metallurgical and Materials Transactions A* **36A**, 725 (2005).
- [15] H. Byounchul, M. K. Young, L. Sunghak, J. K. Nack et. al., *Metallurgical and Materials Transactions A* **36A**, 371 (2005).
- [16] Yu. Hao, *Journal of University of Science and Technology Beijing* **15**, 683 (2008).
- [17] Ran Xu, Cai Qingwu, Jiao Duotian, Wu Huibin, *Transactions of Materials and Heat Treatment* **38**(2), 38 (2009).
- [18] Zhang Peijun, Liu Xianghua, Wang Guodong, *Journal of Northeastern University* **28**(1), 57 (2007).

*Corresponding author: qlh1973@163.com