Effect of Zr, Al Addition on Characteristics of MnS and Formation of Intragranular Ferrite in Non-Quenched and Tempered Steel

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In this paper, the characteristics of inclusions, microstructures and mechanical properties in non-quenched and tempered steel with Zr and Al addition were investigated to compare the effect of ZrO_2 and Al_2O_3 particles on the precipitation behavior of MnS and the formation of intragranular ferrite. The results show that oxides, sulfides and oxy-sulfides in Zr addition steel are all finer than those in Al addition steel. As a result, the volume fraction of intragranular polygonal ferrite (IPF) induced by tiny MnS + V(C, N) particles in Zr addition steel has increased to 14.9%, resulting in higher transverse plasticity. Low lattice mismatch between ZrO_2 and MnS inclusions plays an important role in refinement of MnS inclusions. Besides, the single ZrO_2 particle, which is not wrapped by MnS inclusions, would induce formation of IPF further due to the small mismatch with $\alpha\text{-Fe}$.

KEY WORDS: ZrO_2 ; Al_2O_3 ; MnS precipitation; IPF; non-quenched and tempered steel.

1. Introduction

Non-quenched and tempered (NQT) steel has been widely used in manufacture of automotive parts, such as crankshafts and connecting rods of engine, for its high metal yield, energy saving, simple production process.^{1–3)} For further expansion of use scope, strength and plasticity of steel should be promoted, especially in the steel with large section. For example, the large-diameter bars for crankshafts of lorry, the austenitizing temperature of which would be as high as 1 250°C, would form coarse prior austenite grains after forging. Moreover, in order to avoid the non-uniform properties on large cross section, the forgings are usually cooled in air. As a result, the microstructures of crankshafts of lorry usually consist of intergranular ferrite with large-sized pearlite, which possess poor plasticity.

Utilizing the tiny MnS + V (C, N) particles to induce intragranular polygonal ferrite (IPF) for fine microstructure has been reported in NQT steel before.^{4–6)} But MnS particles are usually precipitated during solidification of steel, with large size and uneven distribution.⁷⁾ Hence, the key point to achieve high volume fraction of IPF is to obtain the tiny and finely distributed MnS particles. In recent years, extensive researches have been performed to realize the goal,^{8–13)} especially after the concept of oxide metallurgy was proposed.¹⁴⁾ Wakoh *et al.*¹⁵⁾ investigated the effect of various oxides in the steel deoxidized with Mn, Si, Ti and Zr on the precipitation of MnS particles. Oikawa *et al.*¹⁶⁾

studied the effect of (Ti, Mn)O oxides on the formation and distribution of MnS inclusions. Zheng *et al.*¹⁷⁾ reported their studies about the Mg/Ti addition on the characteristics of MnS inclusions. But almost all papers were concentrated on the characteristics of MnS inclusions in low-sulfur steels, in which oxides are adequate for MnS heterogeneous nucleation. Up to now, little work has been reported on the effect of oxides on the MnS formation in medium-sulfur NQT steel, especially under condition of low oxygen.

In medium-sulfur NQT steel with low oxygen, oxides for MnS heterogeneous nucleation are relatively insufficient owing to high ratio of S/O. Related studies indicated that Zr addition in steel would generate much larger number of oxides than most other deoxidizers under condition of similar oxygen content, for higher density of ZrO_2 particles.¹⁵⁾ However, there are some opposite views about the effect of ZrO_2 oxides on MnS precipitation. As a type of anionic vacancy oxide, ZrO_2 was not considered as suitable nucleation site for MnS precipitation when oxide metallurgy was proposed.¹⁴⁾ But the similar lattice parameters of ZrO_2 and MnS show that MnS could easily precipitate on the ZrO_2 particles because of low interfacial energy needed.¹⁸⁾

Therefore, the aim of the present work is to elucidate the effects of Zr addition on the precipitation behavior of MnS inclusions. Conventional deoxidizers, *i.e.*, Al alloys were also added in the other steel sample for comparison. The characteristics of inclusions, microstructures and mechanical properties of steel samples were carefully investigated. The relationship between oxides and sulfides and the effects of tiny MnS inclusions on IPF formation were also discussed.

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2. Experimental Procedure

Two 6 kg ingots of NQT steel with Al or Zr additions were melted in a MgO crucible by a vacuum induction melting furnace in laboratory. High purity raw materials were adopted to adjust the contents of C, Si, Mn, P, S and N. The Zr (added by zirconium sponge) and Al (added by aluminum block) were deliberately added into the melts for desired content. The alloys addition procedure was shown in **Fig. 1**. After casted, two ingots were homogenized at 1 200°C for 2 hours and forged into bars with diameter of 40 mm, followed by air cooling to ambient temperature. The cooling rate measured with a BS2400u non-contact infrared thermometer was about 0.3–1.0 K·s⁻¹.

The steels are denoted as Steel 1 (Al addition) and Steel 2 (Zr addition), and the chemical compositions are listed in **Table 1**. The chemical analysis was conducted at the National Analysis Center for Iron and Steel (NACIS), China. Steel 1 is NQT steel without Zr and Al is the major deoxidizer. The content of aluminum is 0.0087 mass% and the content of oxygen is 0.0037 mass%. Steel 2 is Zr-killed NQT steel. The contents of zirconium and oxygen are 0.0092 mass% and 0.0031 mass%, respectively. In addition, 0.0023 mass% Al from the impurities in alloys exists in the Steel 2. The contents of other alloying elements are similar.

The bars were subsequently cut into specimens with size of 12×12×7 mm³, for preparing the inclusion inspection and microstructure characterization. After specimens were ground and polished, the FEI Quanta MLA250 scanning electron microscope (SEM) with an energy dispersive spectroscopy (EDS) was used to determine the inclusions characteristics, such as composition and morphology. Size distributions (length) and number densities of inclusions in longitudinal section have been detected with the EVO18 SEM-EDS equipped with INCA, an automatic analysis software of inclusions. The total area detected in each sample is about 14 mm². For further observation of the inclusions with size less than 1 μm, the JSM-6701F field emission SEM (FESEM) with EDS have been applied.

Microstructures of specimens etched by 3 volume% nital solution were observed by Leica DM4M optical micro-

Fig. 1. Schematic diagram of the alloys addition sequence.

Table 1. Chemical compositions of the sample steels (mass%).

Steel	C	Si	Mn	P	S	V	T. Al	Zr	N	O
Steel 1	0.40	0.57	1.49	0.0068	0.048	0.12	0.0087	—	0.0087	0.0037
Steel 2	0.38	0.57	1.45	0.0076	0.057	0.12	0.0023	0.0092	0.011	0.0031

T. Al means total Al content.

scope (OM) and SEM-EDS. The different microstructure characteristics were measured by a systematic manual point counting procedure. A grid superimposed on microstructure micrographs, covering the sectioning plane of the sample. An unbiased statistical estimation could be obtained after counting the number of placements in different microstructures. The transverse mechanical properties of as-forged steels were also measured at NACIS. The specimens (M6×40 mm) were machined in the transverse direction of the bars.

3. Results

3.1. Optical Microstructure Characteristics and Mechanical Properties

The optical microstructures of the steels are presented in **Fig. 2**. The white network-like structures, shown with black line frame, are grain boundary ferrite (GBF), which are influenced by the prior austenite grain. The white polygonal structures, which distribute inside the GBF, are intragranular polygonal ferrite (IPF). The gray structures are pearlite (P). It is seen that microstructures consist of GBF, IPF and P in both steels. But the amount of IPF in Steel 2 is obviously higher than that in Steel 1. The distribution of IPF in Steel 2 is more uniform as well.

The volume fractions of GBF, IPF and P were measured and the values are listed in **Table 2**. Compared with Steel 1, the amount of IPF in Steel 2 has increased from 6.4 volume% to 14.9 volume% and the volume fraction of GBF

Fig. 2. Microstructure of (a) Steel 1 ×200, (b) Steel 1 ×500, (c) Steel 2 ×200, (d) Steel 2 ×500.

Table 2. Volume fractions of grain boundary polygonal ferrite, intragranular polygonal ferrite and pearlite in the sample steels.

Steel	Volume fractions/%			
	GBF	IPF	GBF + IPF	P
Steel 1	15.2	6.4	21.6	78.4
Steel 2	13.0	14.9	27.9	72.1

has reduced about 2.2%.

The transverse mechanical properties of the bars have been tested and the average values are shown in **Table 3**. It is seen that the tensile and yield strength of both steels are at the similar levels, the values of Steel 1 are a little higher than those in Steel 2. But the elongation and reduction of area of Steel 2 are much higher than those in Steel 1, which means Steel 2 possesses stronger ductility. The differences could result from the higher proportion of the volume fraction of GBF + IPF and the volume fraction of IPF in Steel 2.¹⁹⁾

Table 3. Transverse mechanical properties of the sample steels.

Steel	Yield strength/MPa	Tensile strength/MPa	Elongation/%	Reduction of area/%
Steel 1	865	570	12.3	25
Steel 2	813	527	16.7	39

Fig. 3. SEM micrographs and EDS analysis of IPF grain in (a)–(d) Steel 1, (e)–(j) Steel 2.

3.2. Formation of Intragranular Polygonal Ferrite from Non-metallic Inclusions

In order to figure out the characteristics of the nuclei of the IPF, the microstructures in both steels were carefully observed by the SEM-EDS. The results demonstrate that the IPF structures are induced by the dispersed non-metallic inclusions in steels. **Figure 3** shows the morphologies and EDS analysis of typical inclusions found in both samples.

For Steel 1, there are two typical inclusions found that have the ability to nucleate the IPF, *i.e.* pure MnS inclusions (Figs. 3(a), 3(b)) and compound MnS inclusions with a MnS outer layer and Al-containing oxides core (Figs. 3(c), 3(d)). The IPFs are in irregular polygonal shapes and the sizes are about 10 μm in equivalent diameter. The MnS inclusions inside are ellipsoidal or rodlike and the sizes are about 1–5 μm . Occasionally, more than one particle exists inside of IPF.

For Steel 2, three kinds of inclusions related with IPF have been observed, *i.e.* pure MnS inclusions (Figs. 3(e), 3(f)), compound MnS inclusions which consist of a MnS outer layer and Zr-containing oxides core (Figs. 3(g), 3(h)) and pure Zr–O oxides (Figs. 3(i), 3(j)). As seen in Figs. 3(e), 3(g) and 3(i), it seems that the size of the nuclei has little influence on the size of outer IPF. So, tiny nuclei are preferred to achieve higher proportion of IPF when the volume fractions of inclusions are limited.

In order to further identify the chemical compositions of the particles, the FESEM was applied and the results are shown in **Fig. 4**. V (C, N) particles with a little Ti contained, were found at the edge of the MnS inclusions in both steels. The sizes of most V (C, N) particles are about 0.2–0.3 μm , which are suitable for IPF nucleation.²⁰⁾

3.3. Non-metallic Inclusion Characteristics

As stated above, the IPF structures are generally originated from the non-metallic inclusions in steels. Therefore, samples cut from the longitudinal section were observed with the SEM-EDS to investigate the typical inclusions in

Fig. 4. FESEM micrographs of IPF grain and chemical compositions at the edge of MnS inclusions in (a), (b) Steel 1, (c), (d) Steel 2.

Fig. 5. SEM morphologies and compositions of typical inclusions in the (a)–(e) Steel 1, (f)–(i) Steel 2.

both steels. **Figure 5** represents the observed results and the contents of different elements are decided by atom%.

In Steel 1, the typical inclusions are pure MnS inclusions (Fig. 5(a)), compound MnS inclusions with oxide inside (Figs. 5(b), 5(c)) and Al–O oxides with a small amount of Mg and Mn contained (Figs. 5(d), 5(e)). Owing to the forging process, most pure MnS inclusions and compound MnS inclusions along longitudinal section have been lengthened. Most pure MnS inclusions are in strip shapes, while compound MnS inclusions seem less deformed due to the wrapped oxides. The Al–O oxides are single polygonal or chain shape.

In Steel 2, three typical inclusions have been detected, *i.e.* pure MnS inclusions (Fig. 5(f)), compound MnS inclusions with oxide inside (Figs. 5(g), 5(h)) and Zr–O oxides (Fig. 5(i)). The MnS inclusions are lengthened as well, but most are spindle. The Zr–O oxides wrapped by MnS are obviously smaller than Al–O oxides in Steel 1. From the SEM morphologies of Figs. 5(g) and 5(h), it can be noted that the color of Zr–O oxides is almost the same as the steel matrix. As a result, it is not easy to find Zr–O oxides in samples merely polished. In fact, the Zr–O oxides in Fig. 5(i) were detected in the samples etched by 3 volume% nital solution.

The mean sizes of MnS inclusions (pure and compound) and oxides in both steels have been measured with INCA and results are shown in **Fig. 6**. In Steel 1, the mean size of pure MnS inclusions is 2.94 μm , and the mean size of compound MnS inclusions is 3.16 μm . While the values in Steel 2 are 2.55 and 1.91, respectively, both smaller than MnS inclusions (pure and compound) in Steel 1. Besides, the size of oxides in Steel 1, which mainly consist of Al–O oxides, is larger than Zr–O oxides in Steel 2. It can be inferred that, the number of Zr–O oxides is much larger than Al–O

Fig. 6. Mean sizes of pure MnS inclusions, compound MnS and oxide inclusions in the sample steels.

oxides, because the contents of oxygen are similar in both steels. In short, oxides, sulfides and oxy-sulfides in Steel 2 are all finer than those in Steel 1.

Figure 7 shows number densities of the pure MnS inclusions with different size distribution in both steels. The total number densities are almost the same, but the pure MnS inclusions with size larger than 5 μm in Steel 2 are obviously less than those in Steel 1. The size distributions of compound MnS inclusions in two steels are compared in **Fig. 8**. It is found that tiny inclusions ($< 2 \mu\text{m}$) account for a significant proportion in Steel 2. In contrast, the proportion of inclusions with size less than 2 μm in Steel 1 is much lower. In other words, the tiny MnS inclusions, no matter pure or compound, account for higher proportion in Steel 2.

Figure 9 shows the average aspect ratios of pure MnS inclusions and compound MnS inclusions in both steels.

In Steel 1, the mean aspect ratio of pure MnS inclusions is 3.89, and compound MnS inclusions is 1.99. While the values in Steel 2 are 3.22 and 2.38, respectively. That means the pure MnS inclusions in Steel 2 are more resistant to deformation. However, the compound MnS inclusions in Steel 2 seem more flexible to be elongated than those in Steel 1.

Fig. 7. Size distributions of pure MnS inclusions in the sample steels.

Fig. 8. Size distributions of compound MnS inclusions in the sample steels.

Fig. 9. Mean aspect ratios of pure and compound MnS inclusions in the sample steels.

4. Discussion

4.1. Thermodynamic Calculation of Precipitation

The main inclusions found in the present study are oxides, sulfides and oxy-sulfides. In order to further verify the detection results, the equilibrium precipitation was calculated by Thermo-Calc thermodynamic software with TCFE8.1 database. The total system was set as 100 g. The calculated results of Steel 1 and Steel 2 are shown in Fig. 10. The liquidus temperatures and solidus temperatures in both steels are almost the same, *i.e.* 1 490°C and 1 420°C, respectively. The temperatures of primary precipitates in both steels are presented in Table 4.

In Steel 1, Al_2O_3 particles have been generated in the temperature above 1 600°C. With the decrease of the temperature, the Al_2O_3 particles have transformed to the liquid phase, *i.e.* $(\text{Al}, \text{Mn})(\text{O}, \text{S})$, which would decompose into Al_2O_3 and MnS inclusions at about 1 360°C. MnS inclusions are generated during the last solidification period at

Fig. 10. Generating process of primary precipitations during cooling process, (a) Steel 1, (b) Steel 2.

Table 4. Precipitation temperatures of different phases in the sample steels.

Phases	Al_2O_3	ZrO_2	MnS	$\text{V}(\text{C}, \text{N})$	$\alpha\text{-Fe}$
Precipitation temperature/°C					
Steel 1	>1 600	—	1 425	1 083	780
Steel 2	1 460	>1 600	1 425	1 105	780

about 1 425°C.

In Steel 2, ZrO₂ particles have already existed in the temperature above 1 600°C. A small amount of Al₂O₃ inclusions would be generated at 1 460°C, but the content is so little that could not be found easily in present results. The EDS analysis shown in Fig. 3(h) indicates that a few of Al-containing inclusions indeed exist in ZrO₂+MnS compound particles. MnS inclusions are generated during the last solidification period similarly. So oxides in both steels can act as nucleation sites of MnS inclusions thermodynamically. The results of calculation agree well with the results of actual observation, as shown in Fig. 5.

With the decrease of the temperature, V(C, N) particles are formed in austenite at 1 083°C or 1 105°C, mostly at the edge of MnS inclusions, which are shown in Fig. 4. As the temperature decreases further, proeutectoid ferrites (α -Fe) begin to precipitate at austenite grain boundary or on the inclusions inside of austenite, *i.e.* GBF and IPF, which are presented in Fig. 2.

To sum up, oxides, which are formed in liquid steels, can act as the nuclei of MnS inclusions. Then, V(C, N) particles, which are generated at the edge of MnS inclusions, can induce formation of IPF with the decrease of temperature. The Figs. 10(a) and 10(b) have shown the morphologies of IPF induced by Al₂O₃+MnS and ZrO₂+MnS compound inclusions, respectively. The V(C, N) particles are too small to show in the figure.

4.2. Effects of Oxides on the MnS Inclusions

4.2.1. Nucleation Capability of Oxides

Theoretically, all oxides generated before MnS inclusions begin to precipitate would be the nuclei of MnS inclusions, owing to much smaller nucleation energy needed when heterogeneous nucleation occurs.²¹⁾ However, a few of pure oxides not wrapped by MnS were found in both steels, as seen in Figs. 5(d) and 5(i). The theory of low degree of mismatch^{21,22)} has been used to explain the nucleation ability of non-metallic inclusions. The lower degree of the mismatch, the less interfacial energy needed when MnS inclusions begin to precipitate on the core oxides, which means higher possibility of MnS heterogeneous nucleation. The calculation method adopted was proposed by Bramfitt in 1970.²²⁾ The lattice parameters of MnS,¹⁸⁾ Al₂O₃,²³⁾ ZrO₂¹⁸⁾ and the results are shown in Table 5. It is seen that the discrepancy between MnS and ZrO₂ is only 1.5%, much smaller than the value between MnS and Al₂O₃, which indicates that MnS inclusions are more easily formed on the ZrO₂ particles. As Figs. 6 and 7 shown that, the proportion of compound MnS inclusions in the steel with Zr addition is 17.3%, about twice as large as that in the steel with Al addition (9.7%). It

should be noted that, some compound MnS inclusion could be regarded as pure MnS inclusions because wrapped oxides might not be exposed during the specimen preparation, as schematically shown in Fig. 11. And with the decrease of the oxide size, the inaccuracy would be more serious. The average size of ZrO₂ inclusions in Steel 2 is 0.79 μ m, only about a half of the size of Al₂O₃ inclusions in Steel 1. Hence, it can be inferred that the heterogeneous nucleation ratio of MnS inclusions in Steel 2 is likely more than twice as large as that in Steel 1.

4.2.2. Size of MnS Inclusions

Generally, the elongated MnS inclusions are detrimental to transverse mechanical properties, and the detriment would be more serious with the increase of the size.²⁴⁾ According to the theory of heterogeneous nucleation, the higher heterogeneous nucleation ratio, the lower degree of supersaturation needed when MnS inclusions begin to precipitate, which means the growth rate of MnS inclusions could be lower. As seen in Fig. 6, the mean sizes of pure MnS inclusions and compound MnS inclusions in Steel 2 are both smaller than those in Steel 1. Figure 12 has shown the relationship of misfit between oxides and MnS, the heterogeneous nucleation ratio of MnS inclusions, the size of pure MnS inclusions and compound MnS inclusions. With the decrease of misfit from 8.7% to 1.5%, the heterogeneous

Fig. 11. Schematic diagram of a pure MnS inclusion which is actually compound.

Fig. 12. Relationship of misfit, the heterogeneous nucleation ratio, the size of pure and compound MnS inclusions.

Table 5. Lattice parameters of Al₂O₃, ZrO₂, MnS and discrepancies.^{18,23)}

Particles	Crystal structure	β	Lattice parameter/nm			Disregistry with MnS/%
			<i>a</i>	<i>b</i>	<i>c</i>	
Al ₂ O ₃	corundum	90	0.4758	0.4758	1.229	8.7
ZrO ₂	monoclinic	99.23	0.5145	0.5207	0.5311	1.5
MnS	fcc	90	0.523	0.523	0.523	—

nucleation ratio of MnS inclusions has increased from 9.7% to 17.3%, and the size of pure MnS inclusions and compound MnS inclusions has decreased from 2.94 μm , 3.16 μm to 2.55 μm , 1.91 μm , respectively. The MnS inclusions are much refined after Zr alloys are added into the steel.

4.2.3. Aspect Ratio of MnS Inclusions

MnS inclusions are easy to be lengthened during the forging process, leading to anisotropy in steels.²⁴⁾ So MnS inclusions with low aspect ratio are always preferred. Baker *et al.*²⁵⁾ found that under the same deformation conditions, small MnS inclusions are more resistant to deformation than larger ones owing to their high surface/volume ratio. The aspect ratios of pure MnS inclusions in both steels are plotted against their sizes in **Fig. 13**. The results indicate that, with the sizes of MnS inclusions increasing, the aspect ratios increase. As pointed out in Fig. 8, the average size of pure MnS inclusions in Steel 2 is a little smaller than those in Steel 1 and so is the mean aspect ratio.

However, things are different for the mean aspect ratios of compound MnS inclusions. The average size of compound MnS inclusions in Steel 2 is much smaller than that in Steel 1, but the value of mean aspect ratios is higher instead. It appears, therefore, that the size is not the principal factor which influences the deformation behavior of compound MnS inclusions during hot forging. **Figure 14** has shown

Fig. 13. Relationship between size and aspect ratio of pure MnS inclusions in (a) Steel 1, (b) Steel 2.

more morphologies of compound MnS inclusions in both steels. Generally, oxides are harder than MnS inclusions and not easy to be deformed during forging process.²⁶⁾ When compound MnS inclusions are lengthened with the matrix, the part of MnS near the wrapped oxide is barely deformed and the edge far from the oxide is usually easy to be elongated. It is typical in Steel 1, as shown in Figs. 5(b), 5(c) and 14(a), 14(b), 15(c). However, the ZrO_2 particles in Steel 2, the average size of which is only 0.79 μm , are too small to influence the ductility of ambient MnS inclusions. As a result, the mean aspect ratio of MnS inclusions has decreased more moderately in Steel 2.

4.3. IPF Formation and Mechanical Property

It has been proved that the V (C, N) particles precipitated on MnS inclusion have a B–N relationship with $\alpha\text{-Fe}$, which is critical to the formation of IPF.^{6,20)} Recent researches²⁰⁾ indicate that the size of MnS inclusions has a significant influence on the utilization efficiency of the nuclei for IPF formation and with the increase of MnS inclusions length, the utilization efficiency of the nuclei has been improved remarkably. As stated above, the sizes of pure MnS inclusions and compound inclusions in Steel 2 are both much smaller than those in Steel 1. Hence, higher proportion of IPF was observed in Steel 2.

IPFs induced by oxides were also found in Steel 2. So the disregistries between Al_2O_3 , ZrO_2 and IPF were also calculated and the values are 16.0%²⁷⁾ and 7.4%, respectively, which means Al_2O_3 particles have little ability to promote the IPF formation but ZrO_2 particles are desired. So in Zr addition steel, not only MnS+V(C, N) particles but ZrO_2 particles can serve as the nuclei of IPF. As a result, the volume fraction of IPF in Steel 2 has increased further.

As shown in Table 3, the higher proportion of IPF and finer MnS inclusions in longitudinal section have resulted in higher transverse plasticity. It should be noted that with the proportion of IPF increasing, the proportion of $\alpha\text{-Fe}$ increased at the same time. In consequence, the strength of Steel 2 is a little less than that of Steel 1. In order to achieve high strength and plasticity simultaneously, the content of carbon in steel or the cooling rate after forging, which would influence the proportion of IPF and GBF intensely, need to be further investigated.

To sum up, the ZrO_2 particles generated in Zr addition steel are more effective to refine MnS inclusions than Al_2O_3 particles formed in Al addition steel. The ZrO_2 particles are

Fig. 14. SEM morphologies of compound MnS inclusions in (a), (b), (c) Steel 1, (d), (e), (f) Steel 2.

Fig. 15. Schematic diagram of the relationships between oxide, MnS and IPF in the sample steels.

much smaller in size and larger in number. As a result, the larger proportion of IPF is induced by tiny MnS+V(C, N) particles and higher transverse plasticity is obtained. The relationships between oxide, MnS and microstructure are shown schematically in Fig. 15.

5. Conclusion

In this paper, the characteristics of inclusions, microstructures and mechanical properties have been compared after Al or Zr addition in NQT steels. The conclusions are summarized as follows.

(1) The oxides in Al addition steel are detected as Al_2O_3 , while the oxides in Zr addition steel mainly consist of ZrO_2 particles. The mean size of ZrO_2 particles is only $0.79\ \mu\text{m}$, much smaller than Al_2O_3 particles. Besides, MnS inclusions in Zr addition steel are more tiny than those in Al addition steel owing to lower disregistry between ZrO_2 and MnS inclusions.

(2) IPF formation is discovered in both steels. But in steel with Zr addition, the proportion of IPF is as high as 14.9 volume% due to the larger number of tiny MnS inclusions, resulting in finer microstructures and higher transverse plasticity.

(3) ZrO_2 particles could induce the IPF formation itself,

which play a supplementary role in achieving higher proportion of IPF. Nevertheless, Al_2O_3 particles are inert owing to their high disregistry with $\alpha\text{-Fe}$.

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