

# Ferrite Formation on MnS in Non Heat-treated Steel From Ingot

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**Abstract:** Nucleation position of intragranular ferrite transformation in non heat-treated steel from ingot has been studied by means of optical microscope, SEM/EDS and CMA. Results show that intragranular ferrite also forms on composite inclusion of  $\text{Al}_2\text{O}_3\text{-MnS-V(C,N)}$  in non heat-treated steel from ingot on the basis of dispersing oxides and adjusting sizes, shape and quantity of MnS. Decreasing of Mn content from 1.5 to 0.75% will raise  $\gamma$  to  $\alpha$  transformation temperature by about  $40^\circ\text{C}$  and increase driving force for transformation by about 60J/mol, so nucleation probability of Intragranular Ferrite is increased to over 0.9 relatively. The result is better than previous results, which well compensates the insufficient of previous nucleation position of ferrite in the steel from ingot.

**Key Words:** Non heat-treated steel; Intragranular ferrite; Ingot casting; Nucleation probability

The parts of non heat-treated steel (NHTS) with ferrite-pearlite(F-P) forged at high temperature have low toughness. Although there are papers on improving toughness through fining pearlite by intragranular ferrite (IGF), decreasing carbon and increasing manganese, they are research results from small ingot experiments in lab and continuous casting (CC) process<sup>[1~5]</sup>. The literature indicates that decreasing carbon will urge IGF transformation while an increase of carbon hinders IGF transformation<sup>[5]</sup>. When carbon content is raised for instance to 0.45%, there is no IGF in NHTS<sup>[6]</sup>. For increasing toughness of domestic NHTS with F-P and improving its machinability, author has investigated the principle and the way of producing NHTS with IGF from ingot and solved following three difficult problems: (1) Transformation nuclei of IGF are fewer on the condition of slow solidifying and cooling ingot, as transformation nuclei, oxides and sulfides are coarse and their quantities are reduced compared with CC process and small ingot. (2) Carbon content must be higher in order to attain higher surface hardness of the parts after induction quenching. (3) MnS aspect ratio is less than 5. As a result, ideal IGF is obtained, and NHTS with IGF from ingot has been industrially produced<sup>[8,9]</sup>. This paper observes that increase driving force for transformation and nucleation probability of IGF well compensates the insufficient of nucleation position of ferrite in the steel from ingot.

## 1 Observation and analysis on microstructure and nucleating position of IGF

Microstructure and nucleating position of IGF in steel of 0.48 C;0.42 Si;0.70 Mn;0.053 S;0.10 Cr;0.11 V;0.010 N and 0.0026 O(wt%) is observed and analyzed by optical microscope and SEM/EDS(size of electron beam is  $1\ \mu\text{m}$ ) and CMA respectively.

Preparation of specimens: Squares of 86mm rolled from ingot of 2.3t melted in electric furnace are induction-heated to  $1250^\circ\text{C}$ , and forged to round bars of 65mm. The finish-forging temperature of the round bars is  $1125^\circ\text{C}$  and those bars are cooled to room temperature in air. Samples are cut along radial and axial direction of the bars, then burnished, polished and etched in Nital. Analyzed elements are Mn, Fe, C, O, S. Amount of oxide, MnS and IGF are counted by obtained map.

## 2 Results from observation and analysis

## 2.1 Probability of forming $\alpha$ on intragranular MnS

48 intragranular inclusions are analyzed, in which 28 grains are MnS type of inclusion and 24 grains among them are nucleating position for IGF. Typical example is illustrated in Fig.1. Other four including high Fe and quite low Mn, S are not nucleating position for IGF, which may not have MnS structure. Two grains with compounds of titanium and vanadium are nucleating position and other eighteen non-MnS type grains are totally not nucleating position for IGF.

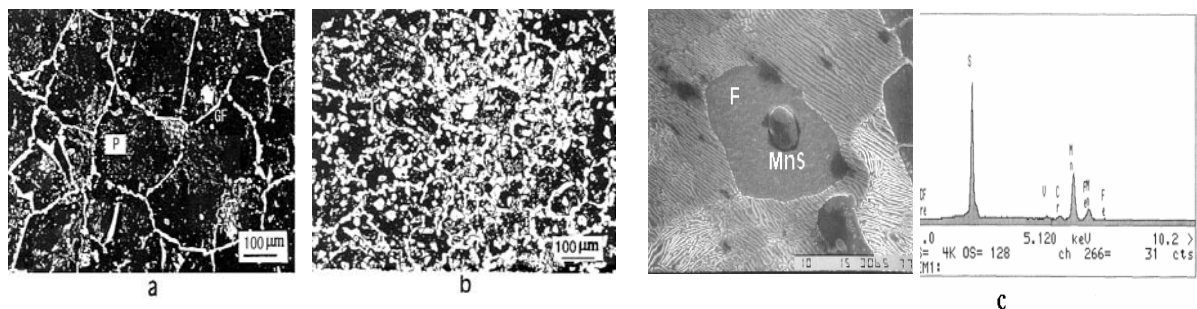


Fig.1 MnS is nucleating position of IGF, (a) (b) optical microscope, (c) SEM/EDS.

Figure 1(a) shows grain boundary ferrite microstructure in steel with same composition without being processed by IGF technique. (a) is for comparison.

## 2.2 Effect of dispersion state of oxide on distribution of MnS

Three vision fields are respectively scanned at  $100 \times 100$  and  $420 \times 420$  spots. Thereafter, distributing map of each element is obtained, illustrated in Fig.2, where the distribution of 5 elements in the area of  $100 \mu\text{m} \times 100 \mu\text{m}$  is shown. Because oxygen exists generally in the form of oxide and S, Mn and Fe exist all in the form of (Mn,Fe)S, the relationship between elements is identical with the one between oxide and MnS. The statistics of 3 two-dimensional vision fields show that oxide is the nucleus of 75%~80% MnS. the result is shown in table 1.

## 3 Discussion on the outcome

### 3.1 Effect of deoxidizing process on quantity of MnS

Although  $\text{Al}_2\text{O}_3$  is not superior in amount, the effect on it by pouring time of liquid steel and solidifying rate is less. Aluminum is taken as main deoxidant in this study. As a result, although oxides in core of practical steel ingot have been coarsened, amount of the oxides as nucleus of MnS is still sufficient. The study is successful.

### 3.2 The confirmation of nucleating position for IGF in the studied steel

Fig.2 and table 1 show that MnS is normally possessed of oxide nucleus. The massive  $\alpha$ -phase but not radial is only observed in the studied steel, therefore  $\alpha$  is coherent relation with V(C,N) [2] and there exist MnS-V(C,N) in IGF(Fig.1c), MnS crystallizing and precipitating on oxide Al<sub>2</sub>O<sub>3</sub>, V(C,N) precipitating on MnS, and  $\alpha$ -phase nucleating on intragranular MnS-V(C,N).

### 3.3 Large probability of nucleating of $\alpha$ -phase on intragranular MnS well makes up insufficient amount of MnS in the studied steel

Table 1 shows that amount of MnS is few in the studied steel. The ratio between the studied amount of MnS and literature [5] data is 1.65:2. According to the probability of 0.56 to 0.64 in literature record [3], the ability of MnS nucleating is considered to be vary high, while transformation probability of intragranular MnS is still greater, more than 0.9, which compensate the insufficiency of amount of MnS in the studied steel. Compared to data in literature [3], the amount of IGF is respectively 24 to 40 and 25 to 43/o.1mm<sup>2</sup> and quite similar

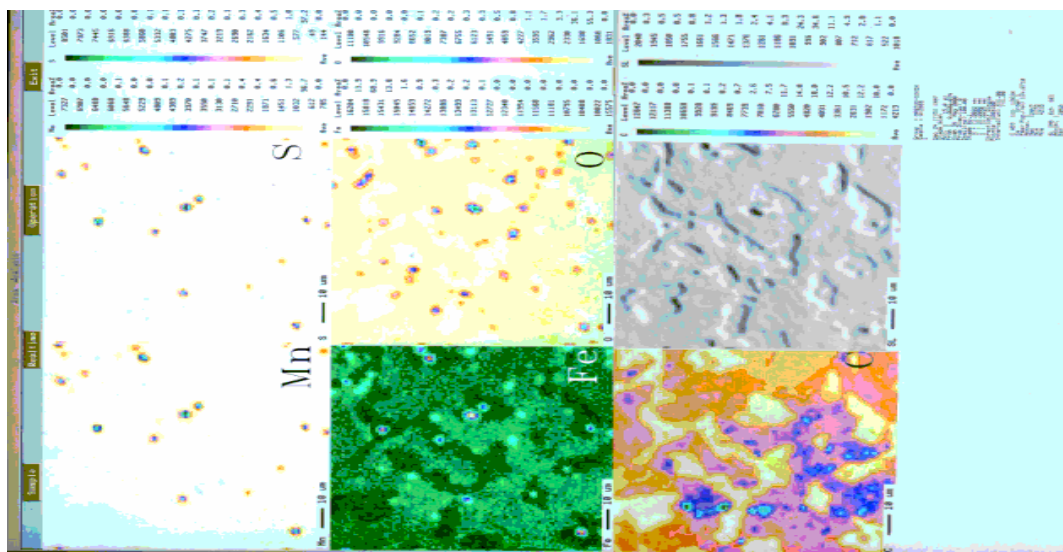


Fig.2 Distributing map of each element, CMA

Table 1 Probability of forming  $\alpha$  on intragranular MnS in NHTS with IGF

Literature	This study	[3]	[10]
Steel melting furnace	30 <sup>4</sup> EF	10kg VIM	
Oxygen dissolved in liquid	Adjusting range	Adjusting range	
Finishing deoxidant	Al	Al	Si、 Mn
Interval between finishing deoxidizing & pouring, min	10	1	1
Ingot weight, t	2.3	≤0.01	Small
Composition C	0.48	0.25	0.25
Mn	0.75	1.50	1.50
S	0.055	0.06	0.06
V	0.115	0.13	0.08

N	0.01	Cutting from	0.01	0.01
Sampling		Bar finish-forging	Cutting from ingot	
Heating of samples, °C		at 1250-1125	1250	1250
		18		
		200		
Cooling rate in air, °C/min			0.7	0.7
Grain size of $\gamma$ , $\mu\text{m}$	①	②	③	
Amount of inclusion/0.1mm <sup>2</sup>	310	350		
(Vision field)	160	170		
Oxide	120	135		
MnS	30	42	25	198
Oxide-nucleated MnS	28	40	24	135
Intragranular MnS (A)				58
MnS in IGF (B)	0.93	0.95	0.96	43
Transformation probability of intragranular MnS, B/A				25
				(55)
			0.74	0.56

### 3.4 Effect of transformation driving force $\Delta G_v$ on nucleating probability of IGF in the studied steel

#### 3.4.1 interface energy

Based on the traditional theory of nucleating<sup>[7,11]</sup>, interface energy can be indicated with structural energy. Fig.3 shows the model of nucleating of  $\alpha$  on x-interface in plane-shape inclusion. It is clear that big  $\sigma_{\gamma X}$  and small  $\sigma_{\alpha X}$  will make  $\alpha$  embryo grow. Free energy  $\Delta G$  will be evaluated by formula<sup>[2]</sup>. Nucleating ability produced by interface energy will increase progressively in following order:, that is spontaneous nucleating-grain boundary-trigonal grain boundary.

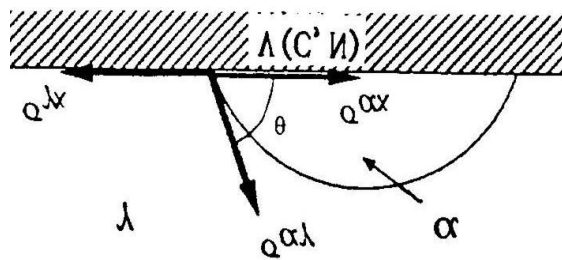


Fig.3  $\alpha$  on plane-shape  $V(C,N)$

#### 3.4.2 Dimensional effect of the inclusion

The studied results collected in literature<sup>[2]</sup> show that nucleating work of each inclusion will be reduced to a peculiar stable value if the inclusions are equal to or greater than  $0.2\mu\text{m}$  in radius. Therefore, it can be taken as nucleating on plane inclusion and there is no dimensional effect of inclusion. Under the continuously cooling condition in this study,  $V(C,N)$  precipitating on MnS can probably reach  $0.2\mu\text{m}$ <sup>[12-14]</sup>.  $V(C,N)$  precipitating in  $\gamma$  is far less than  $0.2\mu\text{m}$  in radius<sup>[7]</sup> without nucleating ability.

### 3.4.3 Critical size ( $d_{crit}$ ) of V(C,N)

Based on analysis in literatures<sup>[7]</sup>, the nucleating work for the nucleus with critical size ( $\Delta G_{crit}$ ) must be reduced to less than maximum  $\Delta G_{crit}$  for grain boundary and triangular grain boundary so as to make  $\alpha$  nucleate in intragranular. Suppose the condition is  $d \geq 2r_{crit}$ , under which  $\alpha$  with a radius  $r$  precipitates on spherical interface of V(C,N) with a diameter  $d$ , the smallest diameter necessary for  $\alpha$  nucleating or the critical diameter is  $d_{crit} = 2r_{crit} = \frac{4G\alpha\gamma}{\Delta G_v}$ . The size of V(C,N) necessary for  $\alpha$  nucleating must be greater than a certain value, which varies with  $\Delta G_v$ . Compared with the transformation point of IGF in the steel with 0.23C-1.5Mn<sup>[13]</sup>, the transformation point of IGF in the studied steel is higher approximately by 40°C. The transformation point affects  $\Delta G_v$  (based on the calculating, steel with 0.75Mn exceeds steel with 1.5Mn in the transformation driving force approximately by 60J/mol<sup>[2]</sup>), thus affects the change of  $d_{crit}$ , and that is to say, smaller V(C,N) may also become the nucleating position for IGF. In a word, Transformation temperature changed by chemical composition to affect  $\Delta G_v$ , resulting in the increase of nucleating points is the main reason for obviously increasing nucleating probability.

## 4 conclusions

(1) IGF can be similarly formed on complex oxide-MnS-V(C,N)inclusion for non heat-treated steel from ingot.

(2) Decreasing Mn content will raise  $\gamma$  to  $\alpha$  transformation temperature. It will increase  $\alpha$  driving force for transformation and nucleation probability of Intragranular Ferrite to over 0.9 relatively. The result is better than previous research data on small ingot and CC, which well compensates insufficient nucleation position of ferrite in the steel from ingot.

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