



Precipitation of titanium nitride inclusions during continuous casting of high carbon wire rod grade steel SWRH 72A

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MS received 24 March 2021; revised 11 October 2021; accepted 9 December 2021

Abstract. The precipitation and growth behavior of titanium nitride (TiN) inclusions during the continuous casting of high carbon wire rod grade steel SWRH 72A was investigated based on the thermodynamic calculations. Titanium is a tramp element in this grade and its pick up in liquid steel mainly takes place from the ladle alloy additions. Titanium in liquid steel is the limiting factor for the growth of TiN inclusions as it diffuses slowly in steel than nitrogen and enriches in interdendritic liquid regions creating favorable conditions for TiN precipitation. It was also observed from this study that the temperature for the formation of TiN inclusion decreased with decrease in titanium for a fixed nitrogen. Titanium nitride inclusions precipitate in steel during solidification even with low titanium and nitrogen content due to the effect of elemental segregation. Solidification segregation of both titanium and nitrogen increased with increase in cooling rate and their segregation tendency increased rapidly with increasing solidification fraction. The effect of titanium, nitrogen and cooling rate on the growth radius of titanium nitride inclusion was studied and validated with actual inclusion measurement.

Keywords. TiN inclusion; thermodynamics of TiN formation; SWRH 72A steel; high carbon steel.

1. Introduction

High carbon grade SWRH 72A steel is widely used in tire cord/bead wire application due to its high tensile strength and ductility. SWRH 72A grade steel is produced at JSW Steel Limited, Bellary, Karnataka, India through Basic oxygen furnace (BOF) followed by argon rinsing station (ARS), ladle heating furnace (LHF) and casted into 165 × 165 mm square billets through continuous casting route. Billets are then reheated to rolling temperature in walking beam furnace and finally rolled to 5.5 mm diameter in wire rod mill followed by control cooling in stelmor conveyor to achieve required ferrite and pearlite microstructure and mechanical properties in wire rods. These wire rods are further drawn to 0.15–0.35 mm diameter through wire drawing at customer end. Hard, non-deformable and angular inclusions such as titanium nitride (TiN) contribute to wire rod breakages during this stage of wire drawing operation and lead to production loss.

Titanium nitride inclusions are non-deformable and have extremely high strength and could cause filament breaks and delamination during wire drawing. These

inclusions also deteriorate the fatigue properties of high carbon wire rods during the service. Tian *et al* [1] reported that the severity of titanium nitride inclusion of size 6 μm on fatigue properties of steel is equivalent to that of oxides with an average size of 25 μm. Titanium nitride (TiN) inclusion in steel can precipitate as a single and independent particle or complex inclusion such as TiN-MnS [2]. TiN inclusions are angular in shape and their color under optical microscope change from orange to pink with increasing carbon content [3]. Titanium nitride inclusions with sharp edges and corners in steel matrix are sources of crack and subsequently contribute to breakage during wire drawing operation. Therefore, the number and size of titanium nitride inclusions in wire rod is to be controlled by controlling liquid steel chemistry and optimize cooling rate of billets during continuous casting. Even though, the complete removal of titanium nitride inclusions in high carbon steel is not practical, it is essential to understand the precipitation behavior of TiN inclusion to control their size and distribution in steel. In the present work, the effect of titanium and nitrogen in liquid steel and solidification rate in continuous caster on the precipitation of titanium nitride inclusions was analyzed to have a better control over TiN inclusion size in high carbon wire rod grade steel.

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Published online: 23 January 2022

2. Precipitation of titanium nitride inclusions in high carbon grade steel

Titanium is not purposefully added to high carbon SWRH 72A grade steel during the steel making process, rather, it is considered as a tramp element. Table 1 shows the variation of titanium and nitrogen of liquid steel during the various stages of steel making. It could be seen from table 1 that titanium in hot metal is relatively high (0.034–0.05%) for all 4 heats and is reduced (oxidized) to 0.0005–0.0012% in basic oxygen furnace (BOF) by oxygen blowing. This indicates that the content of hot metal titanium does not influence the liquid steel (BOF bath) titanium. Titanium pickup in liquid steel was observed to take place due to ladle alloy additions at BOF tapping or during subsequent operations. Ferrosilicon (FeSi) and calcined petroleum coke (CPC) are significant contributors for titanium pickup in ladle. In this study, titanium content of liquid steel in ladle reached to its maximum in all heats after ferrosilicon and/or calcined petroleum coke addition during ladle heating furnace (LHF) operation and dropped during continuous casting as shown in table 1. The drop in titanium in liquid steel is mainly due to its removal to liquid slag as TiO_2 during the argon purging in ladle. Eventually, it could be inferred from the above observations that bath (BOF vessel after oxygen blowing) titanium is considerably low irrespective of high hot metal titanium. Titanium pickup in liquid steel mainly takes place during ladle refining process after ferrosilicon and/or calcined petroleum coke addition.

Two heats from high carbon grade SWRH72A, indicated as heat-A and heat-B in table 1 were considered for this study to investigate the effect of percentage titanium on the precipitation behavior of titanium nitride inclusions during the solidification in continuous caster. The complete chemical compositions of heat-A and heat-B are given table 2.

Heat-A contains 0.0012% final titanium whereas heat-B contains 0.0025% titanium with other elements nearly equal. Study of these two heats compositions enable us to evaluate the effect of percentage titanium on TiN inclusion precipitation kinetics with varying solidification rates for

Table 2. Chemical composition (wt%) of SWRH 72A grade steel (continuous caster).

| | C | Mn | S | P | Si | Ti | N2 |
|--------|-------|------|--------|-------|-------|--------|--------|
| Heat-A | 0.717 | 0.43 | 0.0081 | 0.008 | 0.242 | 0.0012 | 0.0042 |
| Heat-B | 0.715 | 0.46 | 0.0083 | 0.008 | 0.267 | 0.0025 | 0.0038 |

nearly constant nitrogen and carbon contents. Liquidus (T_L) and solidus (T_S) temperatures of grade SWRH 72A are calculated from the chemistry given in table 2 according to equations (1) and (2), respectively [2]. The liquidus and solidus temperatures thus calculated are 1759 K and 1660 K, respectively and these temperatures are nearly identical for both Heat-A and Heat-B.

Liquids temperature in K (T_L)

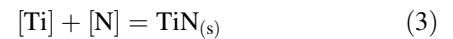
$$= 1811 - [65(\%C)] - [8(\%Si)] - [5(\%Mn)] - [20(Ti)] - [30(\%P)] - [25(\%S)] - [90(\%N2)] - [80(\%O2)] \quad (1)$$

Solidus temperature in K (T_S) = 1538 - [175(%C)]

$$- [20(\%Si)] - [30(\%Mn)] - [40(Ti)] - [280(\%P)] - [575(\%S)] - [160(\%O2)] \quad (2)$$

2.1 Thermodynamics of titanium nitride inclusion precipitation during the solidification of liquid steel in continuous caster

Titanium nitride inclusions precipitate thermodynamically according to the following condition



The change in Gibbs free energy (ΔG°) for the formation of TiN inclusion as per equation (3) is given as [1]

$$\Delta G^\circ = -RT \ln K_{TiN}^E = -291000 + 107.91T \text{ (J/mol)} \quad (4)$$

Table 1. Titanium and nitrogen mapping of four heats during steel making process of grade SWRH72A.

| Heat ID | Element | Chemical composition in wt% | | | | | | |
|---------|----------|-----------------------------|------------|--------|-------------|----------------|-----------|-------------------|
| | | Hot metal | Bath (BOF) | ARS | LHF initial | LHF-in process | LHF final | Continuous caster |
| Heat-A | Titanium | 0.034 | 0.0005 | 0.0008 | 0.0016 | 0.0015 | 0.0013 | 0.0012 |
| | Nitrogen | – | 0.0011 | 0.0017 | 0.0020 | 0.0027 | 0.0037 | 0.0042 |
| Heat-B | Titanium | 0.050 | 0.0008 | 0.0009 | 0.0024 | 0.0028 | 0.0026 | 0.0025 |
| | Nitrogen | – | 0.0012 | 0.0023 | 0.0028 | 0.0030 | 0.0035 | 0.0038 |
| Heat-C | Titanium | 0.044 | 0.0005 | 0.0006 | 0.0025 | 0.0026 | 0.0024 | 0.0023 |
| | Nitrogen | – | 0.0015 | 0.0017 | 0.0027 | 0.0033 | 0.0038 | 0.0047 |
| Heat-D | Titanium | 0.038 | 0.0006 | 0.0007 | 0.0010 | 0.0014 | 0.0012 | 0.0011 |
| | Nitrogen | – | 0.0017 | 0.0026 | 0.0031 | 0.0037 | 0.0044 | 0.0052 |

In the above equation, K_{TiN}^E is equilibrium activity quotient for TiN precipitation, R is universal gas constant (8.314 J/mol K) and T is absolute temperature. Reaction equilibrium activity quotient (K_{TiN}^E) in equation (4) can be calculated from the activities of titanium nitride (a_{TiN}), titanium (a_{Ti}), nitrogen (a_N), weight percentages of titanium (w_{Ti}) and nitrogen (w_N) as given in equation (5).

$$K_{TiN}^E = \frac{a_{TiN}}{a_{Ti} \cdot a_N} = \frac{a_{TiN}}{[(w_{Ti} \times f_{Ti})(w_N \times f_N)]} \quad (5)$$

In equation (5), f_{Ti} and f_N are activity coefficients of titanium and nitrogen, respectively at solidification temperature. The actual change in Gibbs free energy as a function of composition and temperature for the formation of TiN inclusion in wire rod is given as [4]

$$\Delta G = \Delta G^o + RT \log \left[\frac{1}{(f_{Ti} w_{Ti})(f_N w_N)} \right] \quad (6)$$

Gibbs free energy change given in equation (6) can be simplified from equations (4) and (5) as

$$\Delta G = \Delta G^o + RT[-(\log f_{Ti}) - (\log f_N) - \log(w_{Ti} w_N)] \quad (7)$$

Activity coefficients of titanium (f_{Ti}) and nitrogen (f_N) in front of solidifying steel in equation (7) can be calculated from equations (8) and (9), respectively [2].

$$\log f_{Ti} = [(2557/T_{SL}) - 0.365] \log f_{Ti(1873)} \quad (8)$$

$$\log f_N = [(3280/T_{SL}) - 0.750] \log f_{N(1873)} \quad (9)$$

In equations (8) and (9), T_{SL} is the temperature in front of solidifying front, $f_{Ti(1873)}$ and $f_{N(1873)}$ are the activity coefficients of titanium and nitrogen respectively in solidifying steel at 1873 K. Temperature in front of solidifying front of liquid steel (T_{SL}) is in between liquidus and solidus temperatures and can be calculated from equation (10) [2].

$$T_{SL} = T_0 - \frac{T_0 - T_L}{1 - g \left[\frac{(T_L - T_s)}{(T_0 - T_s)} \right]} \quad (10)$$

In the above equation, T_0 is the melting temperature of pure iron (1811 K) and g is solidification ratio or solid fraction.

Activity coefficients of titanium and nitrogen at 1873 K ($f_{Ti(1873)}$ and $f_{N(1873)}$) are estimated from the interaction coefficients of titanium and nitrogen with other elements in steel as per equation (11) and from tables 2 and 3 [2].

$$\log f_{i(1873)} = \sum e_i^j w_j \quad (11)$$

In equation (11), e_i^j is the interaction coefficient of j th element with i th element at 1873 K and w_j is the weight percentage of j th element in liquid steel.

Table 3. Interaction coefficients of e_i^j at 1873 K [2].

| $e_i \setminus e^j$ | C | Mn | N | O | P | S | Si | Ti |
|---------------------|-------|-------|-------|------|-------|-------|-------|-------|
| Nitrogen | 0.13 | -0.02 | 0 | 0.05 | 0.045 | 0.007 | 0.047 | 0 |
| Titanium | -0.19 | -0.43 | -2.03 | -1.8 | 0 | -0.11 | 2.1 | 0.013 |

Gibb’s free energy change (ΔG) for the formation of TiN inclusion is calculated from equations (4)–(11) and tables 2 and 3 as a function of temperature for chemistries of Heat-A and Heat-B. During the solidification of steel, titanium nitride inclusion precipitation is thermodynamically favorable at temperature where the Gibb’s free energy change (ΔG) becomes negative. Therefore, titanium nitride inclusion start precipitates at temperature 1389 K and 1424 K for heats A and B respectively where Gibb’s free energy change is negative ($\Delta G < 0$). This indicates that TiN inclusion precipitates in solid phase region as its equilibrium precipitation temperature is lower than solidus temperature of steel (1660 K). Equilibrium temperature for the formation of TiN inclusion is a function of chemical composition and increases with increase in titanium content in steel keeping all other elements constant. Therefore, in heats with lower titanium, titanium nitride inclusion precipitates at lower temperature and hence its growth is restricted due to low diffusion of titanium and nitrogen at this low temperature that results into low TiN inclusion size in solidified billets.

Free energy change of liquid steel (ΔG) for the formation of TiN inclusion is calculated as a function of temperature and titanium content at 0.004% fixed nitrogen and presented in figure 1. It can be seen from this figure that for fixed nitrogen (0.004%), TiN formation temperature decreases with decrease in titanium content. As already stated, the lower the TiN formation temperature, the lower

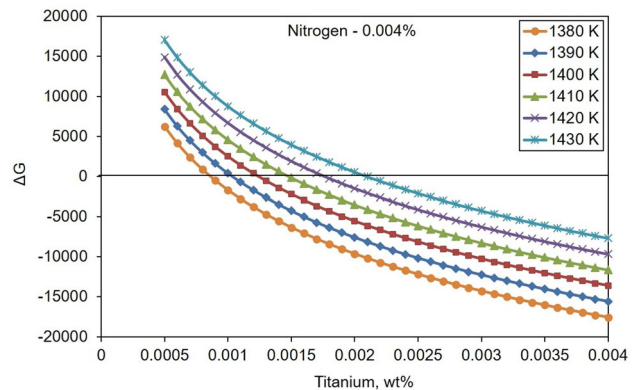


Figure 1. Relationship between TiN formation temperature and equilibrium titanium for fixed nitrogen.

is its growth rate and this result into smaller TiN inclusion precipitate size.

From equations (3)–(7), the concentration (solubility) product of titanium and nitrogen as a function of temperature (T) is given by [1, 5]

$$\log K_{\text{TiN}}^E = \log(w_{\text{Ti}}w_{\text{N}}) = -\frac{15218}{T} + 5.62 \quad (12)$$

The relationship between concentration of titanium and nitrogen for the precipitation of TiN inclusions in steel is evaluated from equation (12) as a function of temperature and is presented in figure 2. TiN inclusion precipitation during the solidification of liquid steel is thermodynamically feasible when the concentration of titanium and nitrogen at solidifying front falls below the equilibrium temperature line as shown in figure 2. It can be seen from equation (12) and figure 2 that for the formation of TiN inclusion in steel having 0.0012% of titanium requires 0.32% nitrogen at solidus temperature (1660 K), which is impossible in actual steel making practice without considering the case of segregation. Kunze *et al* [6] reported that nucleation of TiN inclusion requires high super saturation of elements which can only be attained exceptionally by the segregation in between interdendritic regions.

In the above thermodynamic calculations, it is assumed that liquid steel composition and temperature are homogenous. However, during the actual solidification, redistribution of solute atoms takes place due to the solubility difference between solid and liquid phases. This results in microsegregation of elements in between dendritic arms and promotes TiN precipitation if the temperature and concentration condition in equation (12) is satisfied.

2.2 Solidification segregation of titanium and nitrogen

The solubility of solute atoms dissolved in γ -Fe sharply decreases and their concentration increases continuously in

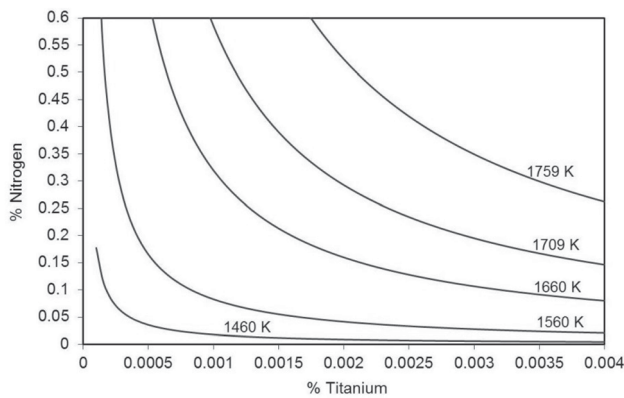


Figure 2. Relationship between equilibrium concentration of titanium and nitrogen as a function of temperature.

between interdendritic regions contributing to segregation in front of the solidification. Ohnaka's equation to calculate the microsegregation of solute in molten steel at different cooling rates during solidification is given by [2, 7]

$$\text{Segregation ratio} \left(\frac{C_L}{C_0} \right) = \left[1 - \left(1 - \frac{\beta k}{1 + \beta} \right) f_s(t) \right]^p \quad (13)$$

where $p = \frac{(k-1)}{\left(1 - \frac{\beta k}{1 + \beta} \right)}$

In the above equation, C_L is the mass fraction of solute in solution at time t (sec) during solidification process, C_0 is original mass fraction of solute in solution, k is equilibrium partition coefficient of solute in liquid and solid phases, f_s is solidification fraction. The value of β in equation (13) can be calculated as $\beta = \frac{4Dr}{L^2}$; where, D is average diffusion coefficient between liquidus and solidus temperatures, L is secondary dendritic arm spacing, τ is local solidification time and R_c is cooling rate (K/min). The secondary dendritic arm spacing L can be computed by $L = 688 \times R_c^{-0.36}$ and the local solidification time τ can be calculated as $\tau = (T_L - T_S)/R_c$ [3, 8].

$$\therefore \beta = \frac{4D\tau}{L^2} = \frac{4D(T_L - T_S)}{R_c [688 \times R_c^{-0.36}]^2} \quad (14)$$

The average diffusion coefficient D in equation (14) is calculated as

$$D = \frac{1}{(T_L - T_S)} \int_{T_S}^{T_L} D(T) dT \quad (15)$$

Substituting T_L , T_S and diffusion coefficient $D(T)$ from table 4, the average diffusion coefficient of titanium in steel can be calculated as

$$D_{\text{Ti}} = \frac{1}{(T_L - T_S)} \int_{T_S}^{T_L} \left[0.15 \times \exp\left(-\frac{250000}{RT}\right) \right] dT \quad (16)$$

Similarly, average diffusion coefficient of nitrogen in steel is calculated as

$$D_{\text{N}} = \frac{1}{(T_L - T_S)} \int_{T_S}^{T_L} \left[0.91 \times \exp\left(-\frac{168600}{RT}\right) \right] dT \quad (17)$$

Table 4. Equilibrium partition coefficient (k) and diffusion coefficient (D) of titanium and nitrogen in γ -phase [1].

| Element | Equilibrium partition coefficient (k) | Diffusion coefficient (D_γ) (cm^2/s) |
|----------|---|---|
| Titanium | 0.33 | $0.15 \exp(-250956/RT)$ |
| Nitrogen | 0.48 | $0.91 \exp(-168490/RT)$ |

Segregation ratio (C_L/C_0) of titanium and nitrogen during the solidification of liquid steel is calculated from equations (13)–(17) at a typical cooling rate 30 °C/min and plotted against solidification fraction (g) for Heat-A as shown in figure 3. Similar result was obtained for Heat-B as the segregation was calculated as the ratio of mass fraction of titanium or nitrogen at any instant to the initial mass fraction of titanium or nitrogen. It can be seen from figure 3 that solidification segregation of both titanium and nitrogen increases rapidly after 90% of solidification. This indicates that even though the average content of titanium and nitrogen in liquid steel is low, it is still possible for the formation of TiN inclusions during solidification due to the effect of elemental segregation. Figure 3 also indicates that with the same solidification fraction and cooling rate, the solidification segregation tendency of titanium is greater than nitrogen due to low diffusivity of titanium. Therefore, titanium is considered as the limiting factor for the growth of TiN inclusions as it diffuses slowly in steel than nitrogen and enriches in interdendritic liquid regions.

During the solidification of steel, solute atoms redistribute due to the solubility difference between solid and liquid phases and that results in microsegregation in between inter dendritic arms. The severity of microsegregation depends on steel chemistry, super heat, casting speed, secondary cooling, EMS (electromagnetic stirring) settings and soft reduction in continuous caster. In the present study, as-cast billets of section 165x165 mm from Heat-A and Heat-B were sliced longitudinally across the center of the billet and the variation of titanium from top to bottom of the billet was measured by optical emission spectrometer. The location of titanium measurement is indicated in figure 4 and the titanium variation across the billet section is presented in figure 5. It could be seen from figure 5 that titanium percentage near to billet center is higher than the average titanium of the heat due to the effect of segregation. Titanium nitride inclusion precipitate in this segregated region when the condition of solubility

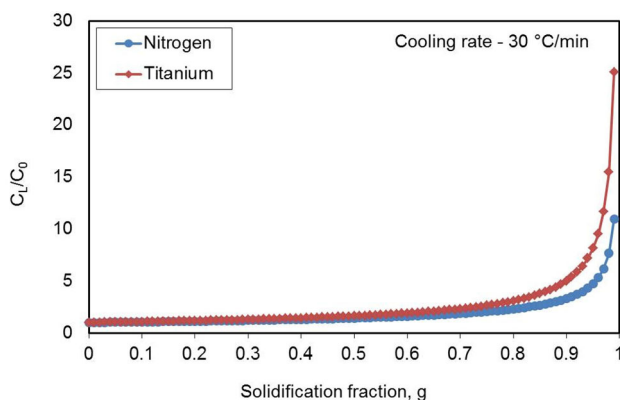


Figure 3. Segregation of titanium and nitrogen during solidification of liquid steel for Heat-A.

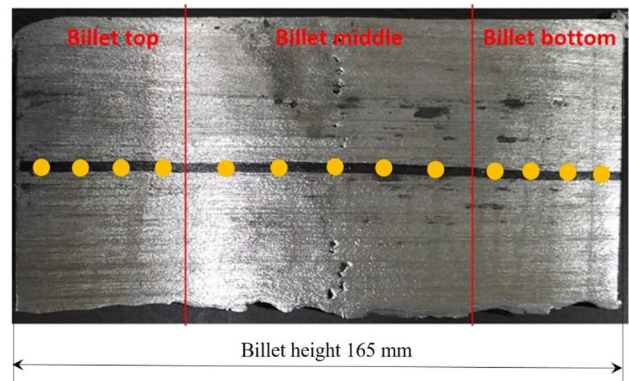


Figure 4. Sample from longitudinal section of billet from Heat-A for titanium segregation measurement. Titanium measurement locations are also indicated on the billet section.

product of titanium and nitrogen described in equation (12) is satisfied.

The intensity of titanium segregation in continuous cast billet was calculated as the ratio of measured titanium at the middle section of billet to the initial titanium (given in table 2). Titanium segregation ratios thus calculated were 1.5 and 1.32 for Heat-A and Heat-B, respectively. These segregation ratios are much lower than the theoretically calculated segregation ratios (C_L/C_0) using equation (13) and presented in figure 5. This difference is due to the fact that during actual solidification, some titanium gets trapped in between inter dendritic arm spacing rather than segregating entirely to the center of the billet. However, during the calculation of segregation ratio using equation (13), it is assumed that all the titanium segregates to the center without any entrapment as it is difficult to theoretically calculate the quantity of titanium that segregates in between dendritic arm spacing.

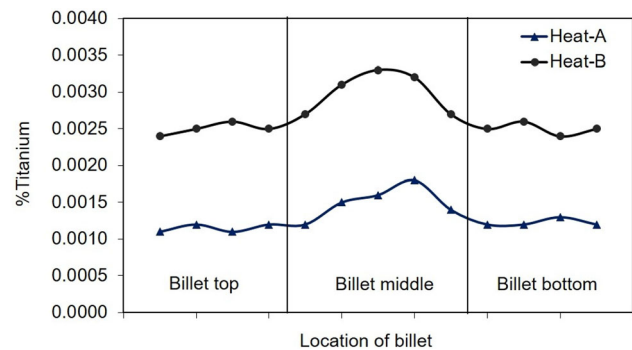


Figure 5. Actual titanium segregation in billet from Heat-A and Heat-B.

2.3 Precipitation and growth of TiN inclusions during solidification

Titanium nitride inclusions precipitate and grow in solid phase region during solidification with an enrichment of titanium and nitrogen due to microsegregation. The difference between the actual microsegregated solute content and the equilibrium solute content is considered to be the driving force for the nucleation and growth of TiN inclusions [9]. Theoretical precipitation size of TiN inclusion during the solidification can be calculated using equation (18) [4].

$$\text{TiN inclusion growth radius in } \mu\text{m}(r) = 10^4 \sqrt{\frac{M_s \rho_m}{50 M_m \rho_s} D_N [w(N_i) - w(N_e)] \tau} \quad (18)$$

M_m -molar mass of iron (56 g/mol), M_s -molar mass of solute (62 g/mol), ρ_m -density of liquid steel (7.07 g/cm³), ρ_s -density of solute (5.43 g/cm³), D_N -diffusion coefficient of nitrogen in γ -steel (cm²/s), $w(N_i)$ -mass fraction of nitrogen in front of the solidifying front, $w(N_e)$ -mass fraction of nitrogen in equilibrium with TiN, τ -local solidification time (s) [4].

Titanium nitride inclusion growth radius is calculated by using equation (18) and the effect of titanium, nitrogen and cooling rate on the growth radius of TiN inclusions is presented in figure 6 for Heats A & B. The growth radius of TiN inclusions increases rapidly at the end of solidification as shown in figure 6. The cooling rate of liquid steel has an obvious effect on the growth of TiN inclusions during solidification. The size of TiN inclusions decreases with the increase in cooling rate from 10 K/min to 200 K/min. For low titanium containing heat-A with 0.0012% Ti, the final TiN inclusion radius at cooling rates 10 and 200 K/min are 8.56 and 2.06 μm , respectively. For high titanium containing heat-B with 0.0025% Ti, the final TiN inclusion radius at the same cooling rates 10 and 200 K/min are 11.29 and 2.74 μm , respectively. Therefore, the size of TiN inclusion in high carbon billet can be reduced by lowering the concentration of titanium in liquid steel and increasing the rate of solidification in secondary cooling zone of continuous caster.

3. Validation of the calculated TiN inclusion size with measured inclusion size in wire rods

Longitudinal samples from 12 randomly selected wire rod coils ($\Phi 5.5$ mm) from both Heat-A and Heat-B were metallographically polished and inspected for TiN inclusions using optical microscope. One such observed titanium nitride (TiN) inclusion was confirmed by SEM-EDS analysis as shown in figure 7 for a coil from Heat-B.

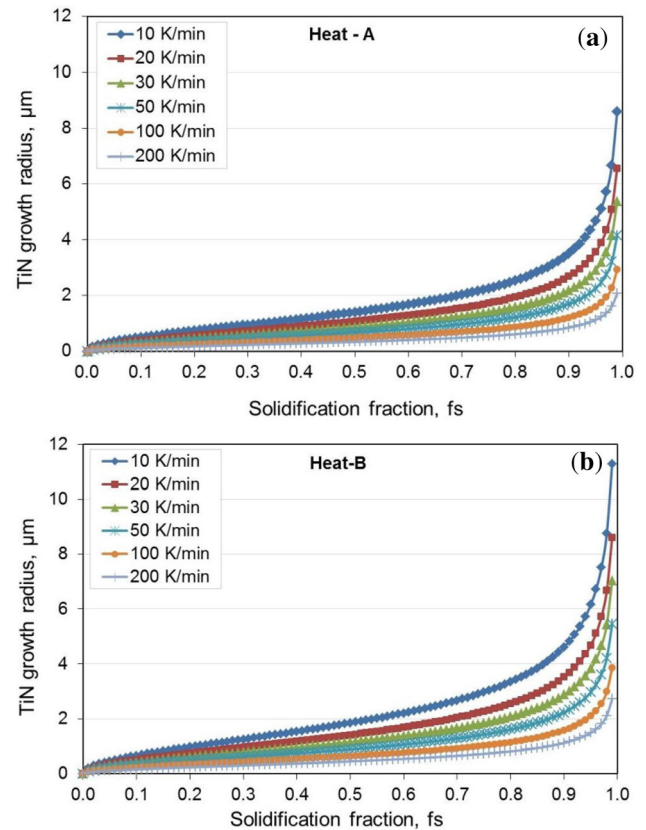


Figure 6. Growth radius of TiN inclusions at different cooling rates for (a) Heat-A and (b) Heat-B.

Figure 8 depicts the largest TiN inclusions size distribution in wire rod coil samples measured using optical microscope for Heat-A and Heat-B. The largest size of TiN inclusions measured in all 12 coils (figure 8) were lower than the thermodynamically calculated inclusion size according to the equation (18) for solidification (cooling) rate 30 °C/min (figure 6). This is because, TiN inclusion size thus theoretically calculated is based on the assumption that all titanium and nitrogen segregates to center of the billet due to solubility difference and then precipitates into TiN inclusion after attaining thermodynamic feasible conditions. However, during the actual solidification, some of titanium and nitrogen get trapped in between inter dendritic arms and precipitate as TiN inclusions after attaining the thermodynamic stable conditions. This reduces the amount of titanium and nitrogen segregation in billet and limits the growth radius of TiN inclusion. Titanium nitride inclusion with size ≥ 4 μm is specified as (customer specification) detrimental to drawability and causes filament breaks during wire drawing operation at customer end. Therefore, faster cooling rates (solidification rate) greater than 50 K/min (figure 6) with titanium in steel less than 0.002% (Heat-A) are suggested for this grade to limit the titanium nitride inclusion size lower than 4 μm .

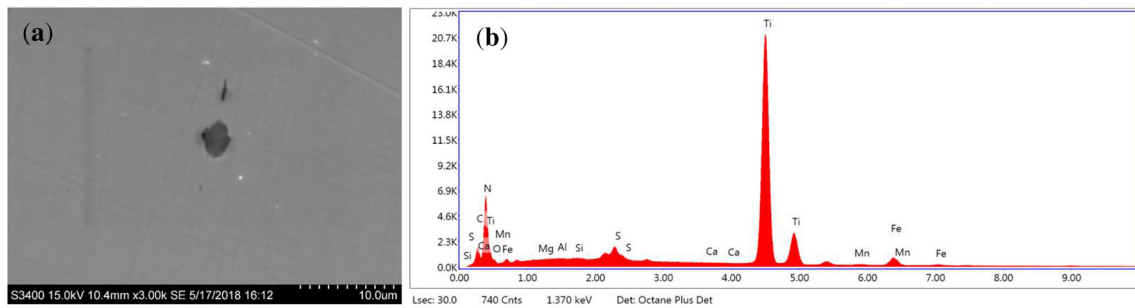


Figure 7. (a) SEM image of TiN inclusion in wire rod sample from Heat-B and (b) TiN inclusion confirmation by SEM-EDS.

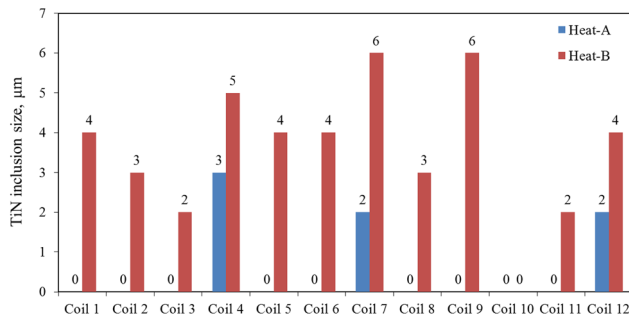


Figure 8. The largest TiN inclusions size (μm) in wire rod coils from Heat-A and Heat-B.

4. Conclusions

Precipitation of titanium nitride inclusions in high carbon wire rod grade SWRH72A was investigated in this study using thermodynamic calculations and the following conclusions were drawn:

1. Titanium nitride inclusion precipitates in solid phase region as its equilibrium precipitation temperature is lower than solidus temperature of steel. This equilibrium precipitation temperature for the formation of TiN inclusion is lowered with decrease in titanium that results in lower TiN inclusion size.
2. Solidification segregation and growth kinetics calculations suggest that solidification segregation of both titanium and nitrogen increases with increase in cooling rate and segregation tendency was greater with increasing solidification fraction.
3. The effect of titanium and nitrogen in liquid steel and solidification rate in continuous caster on the precipitation size of titanium nitride inclusion was studied and validated with actual measurement.

4. Stringent measures of steel making and continuous casting process parameters with faster cooling rates (solidification rate) greater than 50 K/min and titanium in steel less than 0.002% is recommended in this grade to restrict the TiN inclusion size lower than 4 μm .

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