

CHEMICAL METALLURGY CHARACTERISTICS OF STEELS AND THEIR TRANSFORMATION INTO ACICULAR FERRITE

Mazancová E, Jonšta Z., Mazanec K.

TU Ostrava, Institute of Materials Engineering, 708 33 Ostrava-Poruba, CZ

CHEMICKO METALURGICKÉ CHARAKTERISTIKY OCELÍ A JEJICH TRANSFORMACE NA ACIKULÁRNÍ FERIT

Mazancová E, Jonšta Z., Mazanec K.

VŠB - TU Ostrava, Katedra materiálového inženýrství, 708 33 Ostrava-Poruba, ČR

Abstrakt

Byly studovány chemicko metalurgické charakteristiky ocelí a podmínky vzniku acikulárního feritu v uhlíkových ocelích. Nukleační intenzita acikulárního feritu je vyjádřena pomocí různých faktorů, z nichž následující dva hrají velmi významnou úlohu při tomto procesu. Vznik změny chemické volné entalpie, v souvislosti s nukleací feritické fáze podmíněné vznikem na Mn ochuzené zóny v okolí inkluze (Ti_2O_3) při precipitaci MnS. Snížení energie fázového rozhraní doprovázející nukleaci acikulárního feritu na precipitátech TiN, které jsou charakteristické relativně vysokou dosažovanou mřížkovou registrací s feritickou maticí. V práci jsou podrobně analyzovány podmínky pro dosažení dominantní mikrostruktury tvořené acikulárním feritem.

Abstrakt

The inclusions responsible for the preferential acicular ferrite nucleation in carbon steels have been studied. Nucleation rate of acicular ferrite is expressed by various factors from which following two parameters play a very important role in this process. Increase in chemical free enthalpy change for ferritic phase nucleation due to Mn-depleted zone formation in vicinity of Ti_2O_3 inclusions (MnS precipitation). Decrease in interfacial energy accompanying acicular ferrite nucleation on TiN having high lattice registry with ferritic matrix. The conditions leading to the achievement of acicular ferrite as dominant phase in microstructure are analysed.

Key words: acicular ferrite, bainite, non-metallic inclusions, intragranular nucleation, interfacial energy, Mn-depleted zone

1. Introduction

The acicular ferrite (AF) microstructure provides an optimal combination of high strength and good toughness due to refined and interlocked (interwoven) morphology. The achieved higher toughness level in AF microstructure is also related to the increased density of the high-angle boundaries. This property is beneficial, because the above mentioned kinds of boundaries act as obstacles to cleavage and force the cleavage cracks to change the microscopy planes of their growth in order to accommodate the changing local crystallography. In AF microstructures, the density of crystallographically misoriented plates is enhanced as it correspond to increased direct nucleation on potential nucleants [1]. It is generally accepted, the mechanism controlling the austenite (A) decomposition into AF is identical to the mechanism

that controls the bainite (B) formation. The B-particles are nucleated at A-grain boundaries while AF is nucleated intragranularly on non-metallic inclusions or precipitates acting as potential nucleants in steels [2]. The growth of both compared microstructures by the same displacive mechanism dictates that the final microstructure formed in the bainitic temperature range is the competition result between intragranularly nucleated ferritic plates (AF) and B-sheaves nucleated at A-grain boundary surfaces. Formerly realised studies on the factors, making clear the chemical metallurgical principle of enhanced AF formation have led to the conclusion that a reduction in A-grain boundary surfaces per unit volume favours AF nucleation process to the detriment of B-formation. It results from reduced number of the B-potential nucleation sites [3].

A similar effect is obtained by increasing the number of inclusions acting as the AF nucleants. The higher AF volume fraction can also be found if a narrow zone of allotriomorphic ferrite (ATF) forms first at A-grain boundaries. The intergranularly nucleated ATF must be inert in the sense that it should not develop into Widmanstätten ferrite (WF) and B at lower transformation temperatures. This limiting effect depends on carbon-partitioning into A at A/F-interface what leads to the depressing of WF and/or B start temperatures by subsequent cooling process realised below the applied heat treatment temperature [2]. Figure 1 shows the inert ATF interface with A and AF formation in A-grain volume. In contrast to this example, Fig. 2 presents the development of continuously growing WF from ATF zone as it results from the ATF/A active interface behaviour.

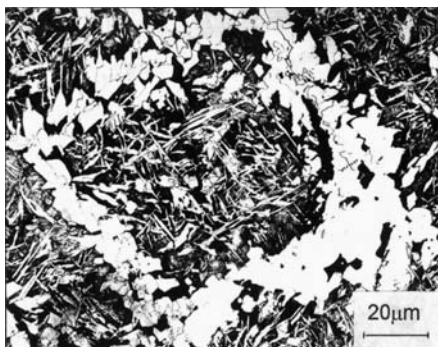


Fig.1 AF microstructure-inert ATF interface with A

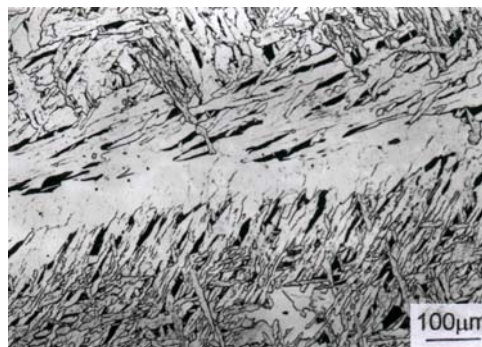


Fig.2 ATF and side plate ferrite microstructure

2. Theoretical background

Several mechanisms have been proposed to explain the way in which non-metallic inclusions are active in AF nucleation. For this reason it is necessary to define more precisely nucleation potency of different at disposal being nucleants. Although the mechanism by which inclusions nucleate AF is not yet elaborated in detail, four possible nucleation variants can be taken into consideration [4]; a) simple heterogeneous nucleation on an inert particle; b) epitaxial nucleation on the inclusions having a good coherency (lattice registry) with ferritic matrix; c) nucleation arising from the strain energy associated with the different thermal expansion coefficient of inclusions and steel matrix; d) nucleation assisted by solute depletion in matrix near inclusions [5, 6]. It depends on the inclusion chemistry and its structure that which mechanism would work to promote intragranular nucleation on given inclusion types. In case of

Ti-oxides (Ti_2O_3), the MnS-depleted zone formation has a very important role in AF nucleation process even though there are much problems to be explained [5].

The aim of this work is to analyse the influence of chosen inclusion types on the intragranular AF-formation. The special attention is paid to the study of steel matrix properties and realised processes leading to the increase in chemical free enthalpy change as it results from the localised Mn-depleted zone formation in matrix around nucleant. Besides above presented analysis the decrease consequences in interfacial energy of intragranularly nucleating particles (inclusions) taking part in AF formation process are evaluated. These nucleation active particles are characterised with relatively high lattice registry with ferrite microstructure. On the contrary, the above discussed nucleation effect of strain energy induced in matrix is weak in comparison with other considered parameters (see b) and d)). For this reason, this influence is not taken in the analysis by the summary evaluation [4, 7].

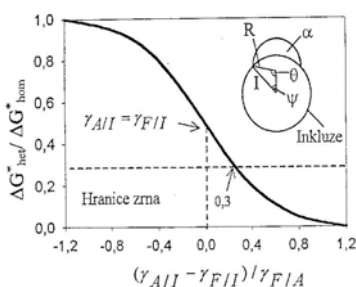


Fig.3 Energy barrier with heterogeneous nucleation as a function of the difference between austenite/inclusion (γ_{AI}) and ferrite/inclusion (γ_{FI}) interfacial energy

3. Influence of non-metallic inclusions on intragranular AF nucleation

Whether the AF interlocked microstructure or the side plate ferrite particles (WF, B) are formed would be determined as a result of mutual competition between potential nucleation sites. This competition process is realised between prior A-grain boundary surfaces and intragranularly acting non-metallic inclusions in A-grain volume. As known, some oxides having higher cations vacancy concentration, e.g. Ti_2O_3 particles, act as precipitation sites for various phases (considered MnS and TiN) in A. Consequently, they become the potential nucleation sites for AF formation. This is due to that iron and the other metallic atoms in the steel matrix diffuse into the oxides on the basis of exchange mechanism between vacancies and atoms. It shows the oxides having higher cation vacancies concentration come into consideration for the realisation of above mentioned process. Among these oxides, Ti_2O_3 can be considered preferentially [8]. The A-grain boundary surfaces are very favourable nucleation sites for B-and/or WF formation, usually. However, certain particles can be active in term of AF-plates nucleation, competing with some advantage with A-grain boundary surfaces. The onset of the A-transformation leading to the primary AF-plates formation takes place at complex particles consisting of MnS which are e.g. surrounded by CuS and/or at Mn and Ti rich oxides. According to Madariaga and Gutiérrez [3], the role of (Mn, Cu)S by the AF nucleation process is related to the different behaviour of A/CuS and AF/CuS interfaces. These basic conditions are schematically presented in Fig. 3. On the other hand, AF nucleation at complex Ti-and Mn-rich oxides is usually associated with the formation of localised Mn-depleted zone in the vicinity to the steel matrix/oxide interface [5, 8].

As expected, the TiN formation is favoured by an increase in the amount of free nitrogen in steel being available for precipitation of given nitride phase. The Ti-addition to steel by deoxidisation process can be bound as Ti_2O_3 after steel solidification. In this case, TiN formation is a result of an exchange reaction with Mn. At low and intermediate nitrogen levels in steel, the $MnOTiO_2$ particles can be formed as it corresponds to the following reaction [8].



At high nitrogen content $(MnO)_2TiO_2$ is more likely reaction product. The applied Ti volume fraction changes the phase composition of obtained inclusion particles. The higher Ti content leads to the reduction amount of $MnOSiO_2$ in steel. The considered Mn-Si phase is substituted with Mn-Ti complex oxides. The type of obtained inclusions is changed in dependence on Ti-content in steel. In case the lowest Ti-addition, the main type is $(MnO)_2TiO_2$ which has near cubic symmetric. On the contrary, after higher Ti-addition in steel, the detected phase is $MnOTiO_2$ having rhombohedral crystallographic structure, very similar to Ti_2O_3 . These phases are characterised with very near lattice parameters what complicates their crystallographic distinguishing process from which other by diffraction pattern analysis. The inclusion type modification, e.g. change from $MnSiO_3$ to Mn-Ti complex oxide phase results in a transition from side plate ferrite microstructure (WF, B) to AF one [4]. Therefore we can conclude, the Mn-Ti oxide particles, especially Ti_2O_3 , have more potency than $MnSiO_3$ for intragranular AF nucleation.

4. Influence of Mn-depleted zone in steel on AF-formation

As shown in Fig. 4, AF in steel containing fine Ti_2O_3 particles nucleates during cooling process at complex precipitates of Ti_2O_3 adhered with MnS and TiN. Contrary to this effect, in steel which does not contain the adhered MnS and TiN particles on Ti_2O_3 , the nucleated AF amount decreases markedly. These results demonstrate, MnS and TiN adhered on Ti_2O_3 contribute greatly to the nucleation of AF and for this reason, it is possible that Ti_2O_3 can also act as "bearer" of above given nucleants. It defines with more precision the Ti_2O_3 role by the AF nucleation process and from this point of view the mechanism of AF nucleation will be discussed. Based on the micrograph presentation (Fig. 4), schematic illustration of the adhered secondary phase precipitates on the Ti_2O_3 and AF transformation way are summarised in Fig. 5 [8]. Simultaneously, this figure indicates, in relation to above given reaction, a possibility how Ti_2O_3 inclusions are modified due to Mn-atoms diffusion from matrix into Ti-oxides [9]. The AF formation at complex precipitate with Mn-depleted zone in term of difference in transformation temperature as it corresponds to the localised increase of chemical free enthalpy change can be held for preferential nucleation process. The TiN effect should also be considered because AF-formation is markedly limited in the absence of the nitride on Ti_2O_3 particles. This effect results from decrease in TiN interfacial energy for AF nucleation. Increased in interfacial energy by ferrite nucleation is $0.20Jm^{-2}$ in case its semicoherent interface with AF matrix. At incoherent interface A/A, this energy reaches to $0.85Jm^{-2}$. The lattice coherency between AF and TiN (FCC) is relatively good, mismatching ratio is as low as 3.8%. The interfacial energy is in this case very low, only $0.15Jm^{-2}$, approximately.

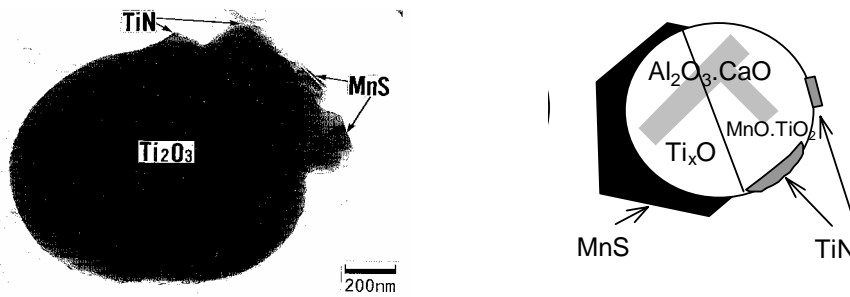


Fig.4 Extraction replica of Ti_2O_3 inclusion with adhered MnS and TiN [5]

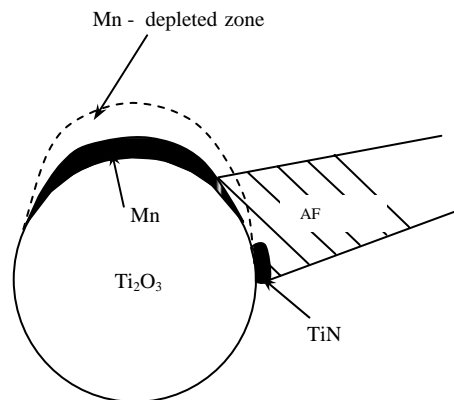


Fig.5 Schematic illustration of inclusion in steel deoxidized with Ti

5. Retarding effect of Si and Al on AF formation

This analysis is devoted to the study of retarding effect due to Al in steel, which is analogical to the Si effect. In this case we can detect $MnSiO_3$ inclusions. It was found, AF nucleation potency of this inclusion type is decreased substantially in comparison with Ti-Mn oxide particles effect. The Ti_2O_3 inclusions only absorb a small amount of Mn at higher Si content in steel. This fact can be ascribed to the strong attractive interaction between Mn and Si atoms in A-structure [10]. The higher content of the Si in steels, the stronger the attractive action between Mn and Si. The Mn absorption in Ti_2O_3 is inhibited at higher Si content in steel. The considered interaction between Mn and Si leads to suppression of Mn segregation in A-matrix [11]. The Ti-level in the oxide particles decreases with increasing Al-content (Fig. 6). The Al has a greater oxygen affinity than Ti and for this reason, Al_2O_3 is likely to replace Ti_2O_3 and increase Al-content. Previously was found, Ti_2O_3 particles are able to absorb Mn-atoms from surrounding steel matrix what results in the Mn-depleted zone formation around Ti-oxides. The Mn-absorption is associated with higher cation vacancy concentration in Ti_2O_3 . Since Al_2O_3 is anion vacancy type oxide, the considered Mn-atoms absorption in this inclusion is not possible. From this reason Al_2O_3 particles might not provide the nucleation sites for AF formation. On the basis of these results, we can conclude, the transition from Ti_2O_3 to Al_2O_3 with increasing Al-content in steel leads to the microstructure type modification. Owing to a shortage of potential intragranular nucleation sites, the transition from AF to B and/or WF microstructure is realised.

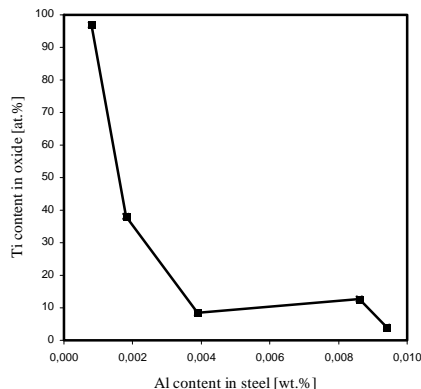


Fig.6 Average Ti-content in the oxide particles (influence of Al in steel) [10]

6. Conclusions

A study has been carried out to clear up the basic chemical metallurgical principles controlling AF formation in comparison with side particles (WF, B) nucleation process. The effect of some inclusions known as potential AF nucleants is taken into consideration. The AF particles are intragranularly nucleated, while the intergranular nucleation corresponds to WF and B initiation. The AF nucleation rate is expressed by two main factors. They are chemical free enthalpy change for development of nucleation process and a decrease in interfacial energy accompanied ferritic phase nucleation on TiN having relatively high lattice registry with AF particles. The effect of Si and Al content in steel on AF formation is analysed.

The present results demonstrate how the change in inclusion types modifies the mechanism of A decomposition into AF to the detriment of WF and B (side plate particles).

Acknowledgement

The results of the project LN00B029 was supported by the Ministry of education of Czech Republic.

Literature

- [1] Gourgues A.F., Flower H.M. and Lindley T.C.: Electron backscattering diffraction study of acicular ferrite, bainite and martensite steel microstructures. *Materials Sci. Technology*, vol.16, 2000, No.1, pp.26-40.
- [2] Babu S.S., Bhadeshia H.K.D.H.: Mechanism of transition from bainite to acicular ferrite. *Materials Trans. JIM*, vol.32, 1991, No.8, pp.679-688.
- [3] Madariaga I., Gutiérrez I.: Role of the particle–matrix interface on the nucleation of acicular ferrite in a medium carbon microalloyed steel. *Acta Materialia*, vol.47, 1999, No.3, pp.4951-960.
- [4] Byun J.S., Shim J.H., Cho Y.W. and Lee D.N.: Non-metallic inclusion and intragranular nucleation of ferrite in Ti-killed C-Mn steel. *Acta Materialia*, vol.51, 2003, No.6, pp. 1593-1606.
- [5] Yamamoto K., Hasegawa T., Takamura J.: Effect of boron on intragranular ferrite formation in Ti-oxides bearing steels. *ISIJ Internat.*, vol.36, 1996, No.1, pp.80-86.

- [6] Shigesato G., Sugigama M., Aihara S., Uemori R. and Tomita Y.: Effect of Mn-depletion on intra-granular ferrite transformation in heat affected zone of welding in alloy steel. *Tetsu-to-Hagané*, vol.87, 2001, No.2, pp.93-100.
- [7] Ishikawa F., Takashaki T., Ochi T.: Intragranular ferrite nucleation in medium-carbon vanadium steels. *Metallurgical and Materials Trans. A*, vol.25A, 1994, No.4, pp.929-936.
- [8] Van der Eijk C., Grong Ø., Walmsley J.: Mechanism of inclusion formation in low alloy steels deoxidized with titanium. *Materials Sci. Technology*, vol.16, 2000, No.1, pp.55-64.
- [9] Shim J.H., Cho Y.W., Chung S.H., Shim J.D., Lee D.: Nucleation of intragranular ferrite at Ti_2O_3 particle in low-carbon steel. *Acta Materialia*, vol.47, 1999, No.9, pp. 2751-2760.
- [10] Shim J.H., Byun J.S., Cho Y.W., OH Y.J., Shim J.D., Lee D.N.: Effect of Si and Al on acicular ferrite formation in C-Mn steel. *Metallurgical and Materials Trans. A*, vol.32A, 2001, No.1, pp.75-83.
- [11] Liu S.K., Shang J.: The influence of the Si and Mn concentration on the kinetics of the bainite transformation in Fe-C-Si-Mn alloy. *Metallurgical Trans.A*, vol.21A, 1990, No.6, pp.1517-1525.