PHYSICAL METALLURGY ANALYSIS OF ACICULAR FERRITE NUCLEATION PARAMETERS IN LOW-CARBON STEELS

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FYZIKÁLNĚ METALURGICKÁ ANALÝZA PARAMETRŮ NUKLEACE ACIKULÁRNÍHO FERITU V NÍZKOUHLÍKOVÝCH OCELÍCH

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Abstrakt

V práci jsou analyzovány fyzikálně metalurgické podmínky intragranulární nukleace acikulárního feritu (AF) v nízkouhlíkové oceli. Nukleace latěk AF je vyvolána na jemných disperzních částicích oxidů Ti (Ti_2O_3). U daného typu oceli se předpokládá, že MnS a TiN jsou vyloučeny na povrchu inkluzí tohoto typu a že přispívají k procesu vzniku AF. Zvýšení chemické volné enthalpie po ochuzení části matrice o Mn vyvolaného po precipitaci MnS na povrchu Ti-inkluzí a snížení energie fázového rozhraní mezi TiN a AF jsou uvažovány jako hlavní parametry iniciace AF. Vliv fázového rozhraní souvisí s vysokou úrovní mřížkové koherence mezi AF a TiN. Vznik ochuzené zóny na Mn může také souviset s difuzí atomů Mn do Ti-inkluzí, což vyplývá ze zvýšené koncentrace kationových vakancí v daném typu inkluzí. Kromě mechanismu ochuzení na Mn vyvolávajícího přednostní rozpad austenitu v uvažované kritické zóně, TiN částice charakterizované nízkou úrovní energie jejich fázového rozhraní s AF laťkami přispívají k rozvoji nukleačního procesu této fáze.

Abstract

The physical metallurgy conditions of intragranular nucleation of acicular ferrite (AF) in low-carbon steel are analysed. The nucleation of AF laths is induced at fine dispersed particles of Ti-oxides (Ti_2O_3) detected in Ti-bearing steels. In given steel category the particles of considered inclusions are adhered with MnS and TiN, which contribute to the nucleation process of AF. The increase of chemical free enthalpy due to Mn-depleted zone formed in austenite after MnS precipitation and decrease in interfacial energy between TiN and AF particles are taken into consideration. The interfacial affect results from high level of lattice registry between AF and TiN. The Mn-depleted zone can be also formed after preferential diffusion of Mn-atoms into considered Ti inclusion category what is connected with high concentration of cation vacancies in these particles. Besides Mn-depletion mechanisms leading to the preferential austenite decomposition in critical zone of austenitic matrix, the TiN particles characterised with low interfacial energy of AF laths can contribute to their nucleation process of this phase.

Key words: acicular ferrite, Mn depleted zone, heterogeneous nucleation, interfacial energy, chemical free enthalpy, non-metallic inclusions.

1. Introduction

More recently, the beneficial effect of some inclusion categories on transformation process in steel has been found. In particular, the intragranular nucleation of acicular ferrite (AF) at non-metallic inclusions is well documented in low-alloy steel weld metals where their beneficial properties are obtained owing to the development of very fine microstructure. The same observations have been also made in wrought steel products. Among many non-metallic inclusions which are known to provide heterogeneous nucleation sites in steel, the preferential attention has been given to Ti-oxides producing very interesting microstructural features of AF in low-carbon steels [1]. The aim of this study is to analyze the physical metallurgy principles influencing the AF nucleation in Ti- bearing low-carbon steels, preferentially the relationship between inclusions and AF nucleation parameters.

2. Theoretical background

In general, a microstructure consisting mainly of AF provides optimum weld metal and/or HAZ and wrought steel mechanical properties, both from a strength and toughness point of view due to their fine grain size and high angle grain boundaries. On the contrary, the formation of large proportion of relatively coarse grain size in allotriomorphic ferrite and side plate ferrite (upper bainite and/or Widmanstätten ferrite) is considered detrimental to toughness as these microstructure types provide preferential crack propagation routes at low temperature (cleavage fracture formation). The AF and the upper bainite are considered to be formed by the same transformation mechanism [2]. In the upper bainite, the ferrite particles are initiated at austenite grain boundaries and characterised with parallel plates having the same crystallographic orientation. On the other hand, AF is nucleated intragranularly at non-metallic inclusions. This nucleation process is accompanied with the sympathetic nucleation what results in the formation of s. c. chaotic arrangement of laths and fine-grained interlocking microstructure of AF [3,4].

The nucleation results detected in Ti-deoxidised steels are encouraging and demonstrate the potentiality of using the concept of intragranular AF formation at inclusions in wrought steels. In such attempts, it must be well understood which phase in non-metallic inclusions of usually heterogeneous character is more effective for intragranular nucleation process and which nucleation mechanisms are realised. Four nucleation processes can be taken into consideration: a) heterogeneous nucleation on an inert particle; b) epitaxial nucleation at the inclusions characterised with a very good coherency with laths of AF; c) nucleation arising from strain energy associated with the different thermal expansion coefficients of inclusions in steel matrix; d) nucleation assisted by solute depletion in the matrix in the vicinity to inclusions. It depends on the chemistry and structure of inclusions that which mechanism would work to promote the intragranular nucleation on inclusion. Ti-oxides are characterised with a high effectiveness by AF nucleation due to a small disregistry with ferrite. In case of Ti_2O_3, the formation of local Mn-depleted zone around this inclusion is considered as additional nucleation effect. These problems will be analysed in detail in one of the next parts of work [5].

3. Effect of inclusions

The non-metallic inclusions play a very important role in the AF-nucleation process. Different inclusion categories have different nucleation ability. Besides the known influences as austenite grain size, density and size of inclusions, the evaluation of furthers parameters including geometry and chemical metallurgy-parameters can be held for very promising [6]. The nucleation potential of inclusions can be determined by measuring the number of AF-laths radiated in fan-shaped form from inclusion surface.

It is known that the low-carbon and/or microalloyed steels contain different inclusion categories, which can include both monophase particles and complex multiphases, for example oxysulphides. In present contribution, the nucleation effect of different volume fraction of MnS, modifying the properties of Ti-oxides, is evaluated. The Ti-oxides represent the nucleation of particles acting as a very important category in the process of AF formation [3,7]. To explain the additional effect of MnS, detected at the surface of Ti-oxides (usually as Ti_2O_3), the level of heterogeneous nucleation ability of this inclusion is analysed. The effect of these oxides containing different MnS volume fraction is evaluated. The performed analysis is realised for the following categories of oxysuphide inclusions: a) Ti-oxides containing less than 5 at.% of MnS designed as Ti-oxides; b) Ti-oxides containing more than 5 at.% (Ti-oxysulphides); c) MnS inclusions containing less than 5 at.% of Ti-oxides are referred as MnS. Ti- oxysulphides exhibit the very beneficial intragranular nucleation potential. These inclusions nucleate the largest number of AF laths having a more elongated shape. The chosen microstructures, presented in Figs 1a, b, demonstrate the examples of different AF lath morphology in dependence on the inclusion category. The AF formation is initiated by the nucleation of laths on inclusions and continued by the edge on face sympathetic nucleation of secondary laths on formerly initiated primary particles.

Although, all considered three categories can act as nucleation sites; the laths initiated at Ti-oxides grow to a shorter distance and not favouring the subsequent sympathetic nucleation of secondary AF laths (Fig.1a). The more elongated AF-laths (Ti-oxysulphides) provide more opportunity for edge on face nucleation and promote the interlocking AF microstructure (Fig.1b). Inclusions referred as MnS have narrow and very elongated form acting as flat surface what leads to the loss in interlocking microstructure. These results show that Ti-oxysulphides possess beneficial nucleation potential for AF formations in comparison with further two mentioned inclusion categories.

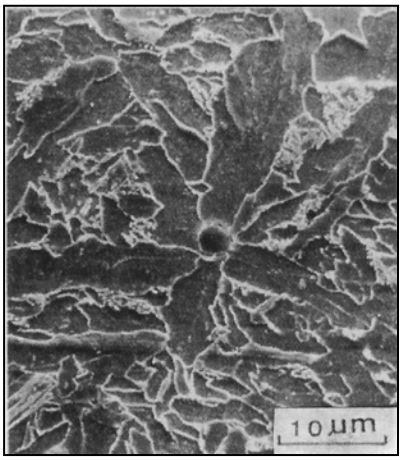

Fig.1a SEM micrograph showing the AF laths around inclusion (Ti-oxide)

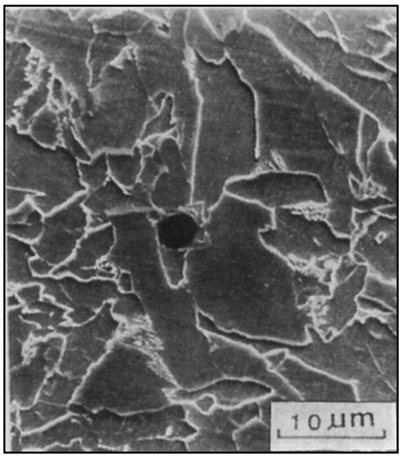

Fig.1b SEM micrograph showing the AF laths around inclusion (Ti-oxysulphide)

Besides above discussed characteristics based on the different morphology of non-metallic inclusions, the following factors can influence the nucleation parameters of the intragranular ferrite formation. Nucleation rate of AF laths depends on the below-stated two characteristics such as chemical free enthalpy change contributing to the nucleation process and on interfacial energy of ferritic and nucleating particles. Sometimes, the strain energy caused by nucleation of ferritic phase is considered, but this effect is held for a very weak and negligible parameter [3].

The influences of MnS and TiN on AF nucleation are expected as major factors. They are as follows: a) an increase in chemical free enthalpy due to the formation of Mn-depleted zone connected with MnS precipitation; b) a decrease in interfacial energy connected with nucleation of AF laths on TiN what results from a very high lattice registry of this phase with ferritic matrix [7].

4. Discussion

4a. Formation of Mn-depleted zone

The schematic illustration of TiN and MnS particles adhered to Ti_2O_3 inclusion are presented in Fig.2. It corresponds to well-known fact that Ti-inclusions (Ti_2O_3) act as potential sites for AF nucleation. The decreased Mn concentration detected in austenitic matrix in the vicinity to MnS precipitated on Ti_2O_3 (considered Ti-bearing low-carbon steel) shows that due to this precipitation process the Mn-depleted zone is formed which is characterised with higher chemical free enthalpy. Besides this depletion mechanism, connected with MnS precipitation, it is also considered that the formation of Mn-depleted is assisted by Mn diffusion into Ti_2O_3 particles. These particles contain higher density of cation vacancies what leads to considerable solubility of Mn in the inclusion matrix. The formation of Mn-depleted zone and connected increase chemical driving force for austenite decomposition in AF results in a preferential promotion of nucleation process by intragranular AF laths initiation at the Ti_2O_3 particles. This in turn gives rise to fine AF microstructure in presented example of Ti-bearing low-carbon steels [2,7].

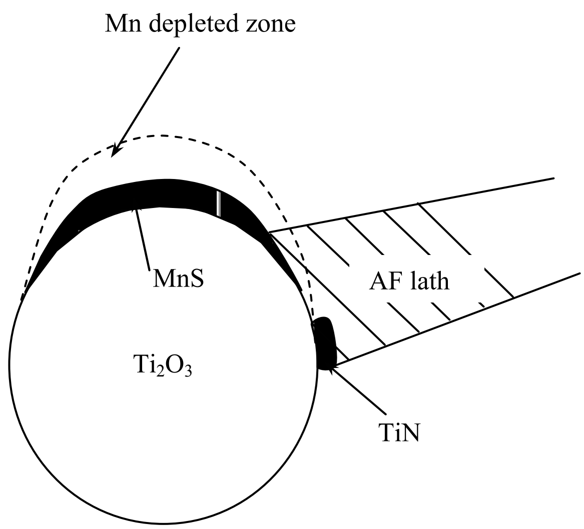

Fig.2 Schematic illustration of chemical metallurgy characteristics around Ti-inclusion

The transformation temperature varies proportionally with Mn content. In case of Mn decrease in steel, Ar_3 transformation temperature rises what is very important for preferential initiation of intragranularly nucleated AF laths. Figure 3 shows the example of Mn-depletion, what in given case corresponds to 10K increase of Ar_3 temperature [7].

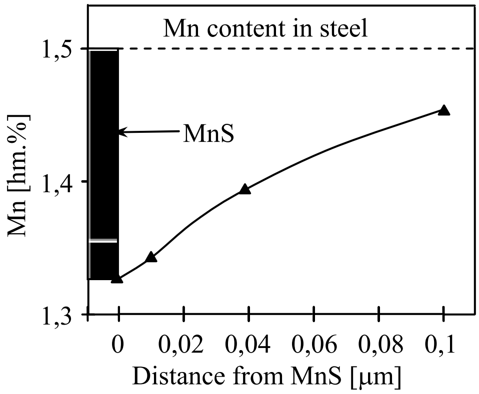

Fig.3 Distribution of Mn concentration in austenite after MnS formation [7]

4b. Influence of interfacial energy between AF and its nucleants

The described influence of Mn-depletion around Ti_2O_3 on the initiation of AF laths, based on the modification in transformation temperature due to local Mn-depletion, can be also developed due to additional nucleating effect of TiN. In this case, it is useful to draw attention to the analysis of physical metallurgy causes resulting from the decrease in interfacial energy connected with TiN precipitation (Fig.2). The level of interfacial energy by ferrite nucleation is 0,20 Jm^{-2} at semicoherent ferrite/austenite interface. In case of incoherent interface this value is higher and reaches to 0,75 Jm^{-2} [8]. The detected lattice coherence between ferrite and TiN is beneficial, because the mismatching ratio is only 3,8 % [7]. The interfacial energy between AF-laths and TiN-particles is very low and its value is only 0,15 Jm^{-2}. This level is lower than the above presented value of 0,20 Jm^{-2} and consequently, it is suggested that TiN-particles promote ferrite nucleation (AF laths formation) effectively.

The relationship between austenite and intragranularly formed AF laths can be explained well as the K-S inter-variant. The detected error, found by the measurement of this relationship, is not exceeding the threshold value of 5° [9].

4c. Influence of Si addition on AF nucleation

The higher Si addition to the low-carbon steel confirms the above-presented idea concerning Mn-absorbtion in Ti_2O_3 inclusion particles from surrounding steel matrix as solid solution. The absorbed Mn-content decreases as the Si-content is increasing. The average Mn-content in Ti_2O_3 particles is plotted in Fig.4 [1]. The performed analysis reveals that there exist strong attractive interactions between Mn and Si atoms in F. C. C. lattice. The higher Si content in steel, the stronger attraction between these elements so that at increased Si contents the Mn absorbtion into Ti_2O_3 is reduced. Liu and Zhang [10] have suggested that the attraction between Si and Mn atoms is strong enough to have a remarkable influence on Mn-segregation to austenite grain boundaries.

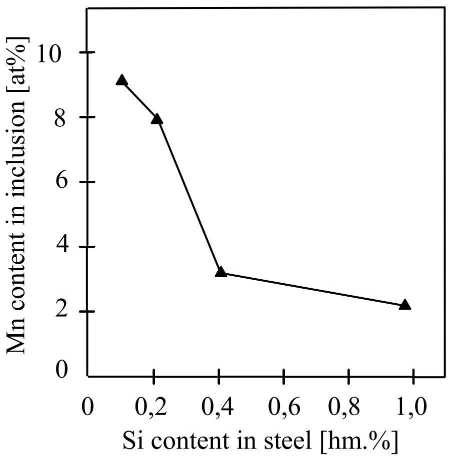

Fig.4 Average Mn content in inclusion of Ti_2O_3 in dependence on Si content in steel

Further, a strong attractive interaction between C and Mn, which is called as C-Mn dipole, exists in steels. High Si-contents also contribute to the formation of greater interaction between C and Mn, what results in the inhibitation of Mn absorbtion, due to Si effect by the enhancement of C-activity in steel. Above presented effects lead to the mobility decrease of Mn atoms and their diffusion into Ti_2O_3 particles [4].

5. Conclusions

The aim of present study is to investigate the physical metallurgy parameters of intragranular nucleation of AF. The attention is devoted to the elucidation of principles influencing the phase transformation of austenitic matrix into AF in Ti-bearing steels. The heterogeneous intragranular nucleation of AF is realised in this steel category preferentially. The study aims to find the physical metallurgy cause both of this preferential action of non-metallic inclusions constituted on the basis of Ti-oxides and the effect of interface behaviour between inclusion and AF lath. The Mn absorbtion process in Ti_2O_3 particles leading to the formation of Mn-depleted zone in the vicinity of these inclusions is analysed.

The relationship between inclusion category and morphology modification of AF is discussed within the framework of this study. The achieved results form a comprehensive basis for further projected studies which are proposed to find a larger set of potential non-metallic inclusion acting as AF nucleants.

Acknowledgement

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