THE BENEFICIAL EFFECT OF INCLUSIONS ON THE AUSTENITE DECOMPOSITION. AND CHEMICAL METALLURGY ANALYSIS OF THEIR INFLUENCE

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Abstract.

The analysis of some inclusion types acting as acicular ferrite plates intragranular nucleates. The comparison with the conditions controlling the intergranular nucleation of upper bainite is included in the performed solution. The demanded parameters put on the chemical metallurgy properties of non-metallic inclusions and on the level of interfacial energy between inclusion and austenite in starting stage and between formed ferritic plates and inclusion. The fundamental data concerning the application of oxide metallurgy concept are discussed. The conditions leading to the formation of fine inclusions and their nucleability behaviour are analysed in detail. The similar ferrite nucleation on oxide inclusion (applied Ti₂O₃ particles) and the effect of secondary inclusions adhered on Ti₂O₃ inclusion surface are taken into consideration.

1. INTRODUCTION

Grain refining is one of the most important characteristic assuring the achievement of toughness improvement of structural steels. In general, a microstructure consisting mainly of acicular ferrite (AF) provides optimal weld metal and HAZ mechanical properties. The study of AF was developed in last time with the aim to produce steels with higher quality presented as beneficial combination of higher mechanical properties (increased strength and toughness) by virtue of microstructure refinement and high-angle boundaries between ferritic plates [1]. On the other hand, the formation of larger proportion of relatively coarse grain boundary allotriomorphic ferrite (ATF) and side plate WF or upper bainite (B) is held for detrimental to
toughness as these structure particles provide preferential crack propagation routes at low temperatures. The AF and upper B are considered to be formed by the same transformation mechanism. In upper B, the basic ferrite initiates at austenite (A) grain boundaries and/or at active ATF/A interface. The products of this A-decomposition process are sheaves of parallel plates having the same crystallographic orientation. On the contrary, AF is nucleated intragranularly at non-metallic inclusions and growing frequently in fan form as it can be detected in numerous events. The nucleation process realized at the inclusions together with the sympathetic nucleation leads to the formation of interwoven microstructure. These secondary ferrite plates are initiated at primary ones under arrangement with low-angle boundaries [2].

These results demonstrate, some non-metallic inclusions play a very important role. The requirement for effective nucleating action is conditioned by special behaviour of inclusions. The thermodynamic parameters and the optimum size of nucleating non-metallic inclusions control the AF nucleation process. These parameters show, the presence of inclusion particles in steel is not at all events detrimental, even in some cases the inclusion particles are nucleants controlling the A-decomposition process into AF.

2. NUCLEATION CONDITIONS OF AF-PARTICLES IN STEEL

The aim of this work is to analyse the influence of chosen inclusion type acting as AF plate intragranular nucleants. The special attention is paid to the study of steel matrix properties and the realized process leading to the increase in chemical free enthalpy change connected with the localized Mn depleted zone formation in the steel matrix. This zone is detected in the immediate neighbourhood of nucleating non-metallic particles. The second effect can be connected with the changes of interfacial energy between inclusion and AF plates. The decrease in interfacial energy between ferritic particles and inclusions has the decisive influence. The nucleation active particles are characterized with relative high lattice registry with AF plates.

The basic conditions of AF nucleation are presented in Fig. 1. The dependence plotted in this figure demonstrates the energy barrier connected with heterogeneous nucleation as a function of the difference between A/inclusions ($\gamma_{A/I}$) and AF/inclusions ($\gamma_{AF/I}$) interfacial energy. As it results from this figure, the necessary condition is high difference between $\gamma_{A/I}$ and $\gamma_{AF/I}$ (according this figure, the nucleation can be detected at minimum value of this
difference around 0.3). The dependence presented in Fig. 1 has been determined in case of 1 µm inclusion diameter [3].

Further, the single parameters influencing AF heterogeneous nucleation process will be discussed in detail. The physical metallurgy properties of different inclusion types will be evaluated. Preferentially, the behaviour of oxides is taken into consideration.

![Energy barrier with heterogeneous nucleation as a function of the difference between austenite/inclusion and ferrite/inclusion interfacial energy](image)

Figure 1. Energy barrier with heterogeneous nucleation as a function of the difference between austenite/inclusion and ferrite/inclusion interfacial energy

### 3. HETEROGENEOUS PRECIPITATION ON OXIDES

The extensive efforts have been devoted to remove the large oxide inclusions already coagulating in steel melt as a result of deoxidizing treatments. These particles are considered as deteriorating products in steel, which unfavourable influence the achieved steel level quality. On the other hand, little attention has been drawn to the function of very fine oxides dispersed in steel matrix which are mostly formed during solidification stage. The performed analysis leads to the conclusion those oxides intragranularly dispersed in steel matrix can be assumed as ingeniously utilized during final A-transformation process. The schematic

![Schematic sequence representation of inclusion formation in Ti-deoxidized steel](image)

Figure 2. Schematic sequence representation of inclusion formation in Ti-deoxidized steel
sequence of non-metallic inclusion formation is presented in Fig. 2. In this figure, the successive regions, corresponding to the processes realized before solidification, during solidification and in solid state (after solidification) are marked out. Simultaneously, Fig. 2 shows stages characterized with prevailing oxide, sulphide and nitride formation. The oxides play a very important role and for this reason, the attention is orientated on the evaluation of those particles by A- decomposition using oxides metallurgy conception [4]. This concept is schematically illustrated in Fig.3.

Figure 3. Basic concept of oxides metallurgy in steels

All criteria, which are summarized in this figure, will not be discussed. The main interest is focused on oxides as nucleation sites in the interior of grains since they are in existence immediately after solidification of melts (defined: formation of intergranular ferrites) [4]. The sequence of inclusion formation describes the behaviour of steel which is desoxidized by Ti-addition. The formed complex inclusion consists besides Ti2O3 of sulphide and nitride [5] Fig. 2).

Some kinds of fine oxides in the interior of A-grains are able to function as nucleation sites for intragranular ferrites. Thus the toughness of steels can be improved through grain refinement by utilizing finely dispersed oxides. The next topic is the oxide which provides with nucleation sites for intragranular AF to attain grain refinement on cooling from A-region without hot working. The phenomenon has been already known with HAZ by welding. The mechanism of the useful nucleant formation is not clear fully. Yamamoto at al. [6] has
shown, both considered MnS and TiN particles precipitate on Ti2O3. This process is indispensable for the intragranular AF formation in this way heat treated steel. Simultaneously, the combination of MnS and VN on Ti2O3 has been found. The important role in this process can be ascribed to the epitaxial nucleation of the plates on nitrides together with the formation of Mn-depleted zone caused by the MnS precipitation on oxides. These results confirm the basic idea, the sulphides and other precipitates really nucleate on oxides. The MnS particles can be detected on some oxides after special nucleation process when the melts were inoculated, e.g. by Ti, MnS has precipitated on the oxides having submicron size.

The above mentioned required size of AF nucleating oxides represents one of the decisive parameters [3].

4. BASIC PROPERTIES OF OXIDES

The aim of the presented discussion is to try to clear up the chemical metallurgy nature of oxides acting as potential AF plate nucleants. Dispersed oxides play diversified roles in steels, but all the oxides may not be able to function as sites for secondary precipitation. It is likely, that each oxide has some different degree of compatibility with the precipitated particles [4].

On way how to solve this situation is the classification the oxides into two categories (active and inactive for preferential precipitation) depending on the ease and/or the difficulty with which the cation diffusion due to higher density of cation vacancies in the oxides is realized. Under active oxides can be included e.g. Ti2O3, TiO2, MnOTiO2 etc. As inactive oxides act the oxide particles having increased density of anion vacancies (Al2O3, SiO2, ZrO2). The higher vacancy density in Ti2O3 contributes to the diffusion (mobility) of cations from matrix into the neighbourhood oxides characterized with higher cation vacancies. In this case, the direct Mn-diffusion into Ti2O3 can be realized as an additional process leading to the Mn-depleted zone formation [1, 6].

As is well known, cation sites in cation-vacancy oxides (simple oxides e.g. Ti2O3, TiO, FeO) involve much vacancies and other considered complex oxides as MnTiO3 are probably at the same state. On one hand, oxides of anion- vacancy type may allow the interdiffusion of oxygen from matrix into the oxide and are not active as the site for precipitation process. However, in case the degree of supersaturation is sufficiently large, coarser oxides having broader grain boundaries could provide with the site for precipitation, even if the oxides are of the anion.-vacancy type [4].

The Ti level in the oxide particles decreases with increasing Al content (Fig. 4). The Al has a greater oxygen affinity than Ti and for this reason Al2O3 is likely to replace Ti2O3.
Previously has been found, Ti$_2$O$_3$ particles are able to absorb Mn-atoms from surrounding steel matrix what results in the above mentioned Mn-depleted zone formation around Ti-oxides [7]. The Mn-absorption is associated with brighter cation vacancy concentration in Ti$_2$O$_3$. Since Al$_2$O$_3$ is anion vacancy oxide type, the considered Mn-atoms absorption is this inclusion is not possible. From this reason, Al$_2$O$_3$ particles might not provide the nucleation sites for AF formation. On the basis of these results, it is possible to conclude the transition from Ti$_2$O$_3$ to Al$_2$O$_3$ with increasing Al-content in steel leads in the microstructure modification. Owing to a shortage of potential intragranular nucleation sites, the transition from AF to upper B and/or WF microstructure is realized [8].

![Graph showing Ti content in oxide particles vs. Al content in steel](image)

Figure 4. Average Ti-content in the oxide particles (influence of the Al in steel on the reduced Ti$_2$O$_3$ formation [7])

5. ANALYSIS OF INCLUSION SEQUENCE IN TI-DEOXIDATION STEEL

Figure 2 summarises the sequence of inclusions formation after application of Ti-additional steel deoxidization. In the melt stage, strong deoxidizing elements Al and Ca were applied. These elements react with dissolved oxygen in the liquid steel to form core of inclusions acting as a basis on which the Ti oxides grow epitaxially during solidification process. During the final stage of solidification some MnS precipitation occurs due to pinning reaction realized in interdendritic regions enriched with segregating element, e.g. S. The remaining S precipitates on the oxides as MnS in the solid state. At even lower temperatures, TiN becomes a stable phase. Provided that free Ti atoms are present in the matrix, pure TiN may nucleate and grow directly in the austenite. Conversely, if most of Ti is already tied up in the oxide core, the TiN formation is a result of exchange reaction product with Ti$_2$O$_3$. This gives MnOT$_2$ as a secondary reaction product with Mn being absorbed from adjacent steel matrix [5]. The Mn compound formation at the surface of the inclusions leads to the
formation of Mn depleted zone (due to MnS formation). The direct Mn diffusion into inclusion containing Ti$_2$O$_3$ represents the second variant resulting in Mn-depleted zone [6, 8].

6. CONCLUSIONS

The study has been carried out to clear up the fundamental chemical and physical metallurgy principles controlling AF formation. The comparison with side particles (upper B, WF) nucleation process is included in present solution. The conditions leading to the fine oxide particles formation are analyzed by application of oxides metallurgy concept. The intragranular AF nucleation is in majority of cases realized on fine oxide particles (having diameter around 1 µm) which adhere inclusion as MnS and TiN in addition. The Ti-oxides (Ti$_2$O$_3$) act as bearer of additional inclusions which are situated on the surface of this oxide inclusion. These complex inclusions are characterized with increased AF nucleation activity in comparison with single Ti$_2$O$_3$. The principles of oxides metallurgy concept in relation to the oxides nucleation activity (Ti$_2$O$_3$) are discussed. The chemical metallurgy consequences of this nucleability process from print to view of A-decomposition into AF are included in present work.

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REFERENCES