

Effect of Cerium Addition on the Evolution of Non-Metallic Inclusions in Steel – A Literature Review

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Abstract

Rare earth elements (REE), particularly cerium (Ce), are widely used as alloying additions in modern steelmaking due to their strong chemical activity and high affinity for oxygen and sulphur. Their ability to react with impurities allows the effective modification of non-metallic inclusions, enhancing steel microstructure and overall performance. This review focuses on the ways cerium interacts in steel, highlighting transformations of inclusions such as Al_2O_3 and MnS , as well as complex systems like Ce-Al-O , Mn-O-S , and Ce-Ca-Al-O . Particular attention is given to the thermodynamic aspects of inclusion evolution and their dependence on processing conditions. The influence of cerium on sulphide stress cracking (SSC) resistance, solidification microstructure, and mechanical properties is also examined. According to the literature, the optimal cerium content is generally 0.01–0.02 wt.%, while higher amounts can negatively affect material performance.

Keywords:

steel, thermodynamic, modification, non-metallic inclusions, sulphides, oxysulphides, cerium

1. INTRODUCTION

Non-metallic inclusions are a major factor limiting steel performance, especially in applications that demand high fatigue strength and corrosion resistance under aggressive conditions. Complete removal of these inclusions from molten steel is not feasible due to technological limitations. Consequently, modern steelmaking focuses on controlling and modifying inclusions to mitigate their negative effects. One of the most effective strategies is the use of rare earth elements, especially cerium. Cerium promotes the transformation of non-metallic inclusions and contributes to improved steel properties. It has a melting point of 799°C and a density of 6,770 kg/m³ and shows relatively high solubility in ferrite (0.1–0.5%) but low solubility in austenite (~0.04%) [1–3]. In steel, cerium primarily acts as a deoxidiser and desulphuriser, binding low-melting-point impurities such as arsenic, lead, tin, or antimony to form stable compounds including oxides, oxysulphides, sulphides, and nitrides. It also modifies existing inclusions by influencing their chemical composition, morphology, and physicochemical properties, which improves their deformability and enhances the corrosion resistance of the steel. Another important aspect of rare earth elements is their effect on solidification. Small additions of cerium can refine the solid phase and strengthen the steel through phases with limited solubility in the α - γ system. REE additions can also enhance tensile strength by affecting crystallisation and promoting the formation of the

γ -Fe eutectic, which alters the solidification temperature [4]. The effectiveness of cerium in modifying inclusions depends on the sulphur-to-oxygen ratio in the steel and the amount of additive [5, 6]. Research on the fundamental mechanisms of inclusion evolution in REE-modified steels is still limited. The high reactivity of cerium complicates precise metallurgical control, potentially causing issues such as clogging of casting channels during pouring. Cerium also tends to segregate in interdendritic regions during solidification, forming clusters of cerium-rich inclusions. Therefore, its impact is strongly influenced by technological factors such as the deoxidation method, alloy composition, and solidification conditions.

2. THERMODYNAMICS AND KINETICS OF CERIUM REACTIONS IN STEEL

Cerium is a highly reactive element with a strong affinity for oxygen and sulphur, which leads to the formation of stable phases such as Ce_2O_3 , $\text{Ce}_2\text{O}_2\text{S}$, CeS , Ce_3S_4 , and Ce_2S_3 [4–13]. The three-dimensional equilibrium activity diagram of oxygen, sulphur, and cerium (Fig. 1) illustrates how the reactions involving these elements proceed as a function of their concentration ratios. At low concentrations of cerium, oxygen, and sulphur (Ce, O, and S), their activities are strongly influenced by variations in their concentrations. The equilibrium surfaces for cerium oxide (Ce_2O_3), cerium oxysulphide ($\text{Ce}_2\text{O}_2\text{S}$), and the cerium sulphides CeS , Ce_3S_4 , and Ce_2S_3 are shown in Figure 1. The

DEF curve defines the composition of the metal alloy in which cerium oxysulphide ($\text{Ce}_2\text{O}_2\text{S}$) is in equilibrium with the three sulphides. At points E and F, the oxysulphide is in equilibrium with two adjacent sulphides. When the oxygen content in the alloy lies within the equilibrium field of cerium oxysulphide ($\text{Ce}_2\text{O}_2\text{S}$), the addition of cerium results in the immediate precipitation of the oxysulphide. The composition of an alloy containing enough cerium shifts towards the DEF line, along which sulphide precipitation begins simultaneously.

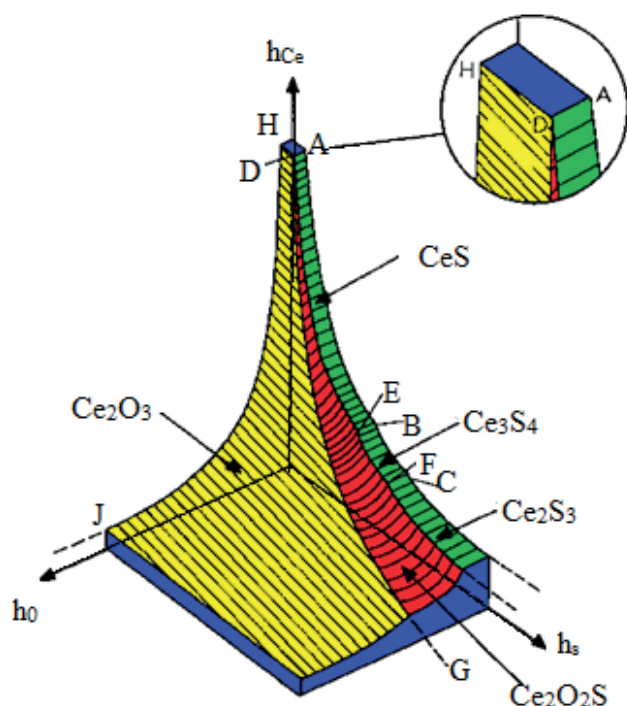


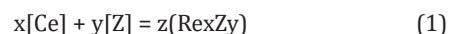
Fig. 1. Ce–O–S equilibrium system [5, 9, 11]

Table 1

Standard Gibbs free energy ΔG° for the reactions of cerium [9, 14–26]

Reaction	Formula no.	$\Delta G^\circ = A+B \text{ [J}\cdot\text{mol}^{-1}]$
$[\text{Ce}] + [\text{O}] + 1/2[\text{S}] = 1/2\text{Ce}_2\text{O}_2\text{S}(\text{s})$	(4)	$-675,700 + 165.5T$
		$-676,795 + 166T$
		$-675,700 + 164.45T$
$2[\text{Ce}] + 2[\text{O}] + [\text{S}] = \text{Ce}_2\text{O}_2\text{S}(\text{s})$	(5)	$-1,352,700 + 331T$
$[\text{Ce}] + [\text{S}] = \text{CeS}(\text{s})$	(6)	$-394,428 + 121T$
		$-422,100 + 120.38T$
		$-422,780 + 121T$
		$-422,783 + 120.58T$
$[\text{Ce}] + 3/2[\text{O}] = 1/2\text{Ce}_2\text{O}_3(\text{s})$	(7)	$-3,944,428 + 121T$
		$-714,380 + 185.67T$
$3[\text{Ce}] + 4[\text{S}] = \text{Ce}_3\text{S}_4(\text{s})$	(8)	$-715,560 + 180T$
$[\text{Ce}] + 4/3[\text{S}] = 1/3\text{Ce}_3\text{S}_4(\text{s})$	(9)	$-1,494,441 + 439T$
		$-497,670 + 146.37T$
$[\text{Ce}] + 3/2[\text{S}] = 1/2\text{Ce}_2\text{S}_3(\text{s})$	(10)	$-498,480 + 146T$
		$-536,420 + 112.16T$
		$-536,420 + 163.86T$
		$-537,290 + 164T$

Simrnov at al. confirm that Ce can be added to molten steel over a broad concentration range at low Ce concentrations in liquid steel (up to 0.1%), because cerium primarily reacts with oxygen and sulphur [1]. Higher additions promote the formation of oxide and sulphide phases and can also neutralise other detrimental elements such as phosphorus and copper, as well as interact with nickel and iron. The final composition of non-metallic inclusions is strongly influenced by the oxygen and sulphur content in the steel. The formation of inclusions occurs according to the following reaction Scheme (1). The equilibrium constants for the reaction are expressed by Equations (2) and (3) [5, 9].



$$\Delta G^\circ = A + BT \quad (2)$$

$$\Delta G = \Delta G^\circ + RT \ln K \quad (3)$$

where:

[Z] – element dissolved in liquid steel,

ΔG° – standard Gibbs free energy of forming a non-metallic inclusion with Ce,

T – temperature,

R – gas constant,

K – equilibrium constant of the reaction,

A, B – constants.

Formation reactions can be summarised as shown in Table 1, which presents the reactions and standard Gibbs free energies (ΔG°) for cerium compounds. This indicates that Ce_2S_3 , Ce_3S_4 , and Ce_2O_3 can transform into $\text{Ce}_2\text{O}_2\text{S}$ and CeS , explaining why only these two phases are typically observed in steel. The Gibbs free energy (ΔG) for $\text{Ce}_2\text{O}_2\text{S}$ is significantly less than zero and lower than that of other inclusions, making $\text{Ce}_2\text{O}_2\text{S}$ the most likely phase to form in steel. Table 2 also presents the element interaction coefficients $e(i/j)$ of the components in the steel.

Table 1 (cont.)

Reaction	Formula no.	$\Delta G^\circ = A+B [J \cdot mol^{-1}]$
$[Ce] + 2[O] = CeO_2(s)$	(11)	$-852,720 + 249.96T$
		$-854,274.7 + 249T$
		$-853,600 + 250T$
$2[Ce] + 3[O] = Ce_2O_3(s)$	(12)	$-1,430,200 + 359T$
$Ce_2O_2S(s) + [O] = Ce_2O_3(s) + [S]$	(13)	$-77,500 + 28T$
$[Ce] + [Al] + 3[O] = CeAlO_3(s)$	(14)	$-1,366,460 + 364T$
		$-1,366,460 + 364.3T$
$Ce_2S_3(s) + [Ce] + [S] = Ce_3S_4(s)$	(15)	$-420,541 + 113T$
$[Ce] + 5/2[O] + 1/2[Si] = 1/2Ce_2O_3(s) + SiO_2(s)$	(16)	$-1,106,635 + 286.11T$
$2[Ce] + Al_2O_3(s) = 2[Al] + Ce_2O_3(s)$	(17)	$-1,073,900 + 326T$
$[Ce] + 5/2[O] + 1/2[Si] = 1/2Ce_2O_3(s) + SiO_2(s)$	(18)	$-1,106,635 + 286.11T$
$[Ce] + 1/2[S] + 1/2CaOAl_2O_3(s) = 1/2Ce_2O_2S(s) + [Al] + 1/2[O] + 1/2CaO(s)$	(19)	$-78,057 - 22.24T$
		$-982,839 + 247T$
$Ce_2O_3(s) + [S] = Ce_2O_2S(s) + [O]$	(20)	$77,360 - 28.48T$
		$38,680 - 14.24T$
$[Ce] + Al_2O_3(s) = CeAlO_3(s) + [Al]$	(21)	$-23,900 - 247.30T$
		$-423,900 - 247.30T$
$[Ce] + [N] = CeN(s)$	(22)	$-401,200 + 153.0T$
$[Ce] + 1/2CaOAl_2O_3 = 1/2Ce_2O_3 + 1/2CaO + [Al]$	(23)	$-1,021,604 + 262T$

Table 2

Element interaction coefficients $e(i/j)$ [9, 18]

$e(i/j)$	C	O	S	P	Si	Mn	Al	N	Ce	La
O	-0.45	-0.20	-0.133	0.07	-0.131	-0.021	-3.90	0.057	-12.1	-12.1
S	0.11	-0.27	-0.028	0.029	0.063	-0.026	0.035	0.01	-1.88	-2.79
Ce	0.351	-106	-8.225	1.77	-	0.13	-2.67	-	0.0066	-
Mn	-0.07	-0.083	-0.048	-0.035	-3.0	0	-2.4	-0.091	-0.5	-
Al	0.091	-6.6	0.03	0.033	0.0056	0.035	0.045	-0.053	-6.1	-0.511
Si	0.18	-0.23	0.056	0.11	0.11	0.002	0.058	0.090	-7.7	-
La	-0.279	-105	-12.13	1.734	-	0.28	-2.649	-	-	-0.013

The equilibrium lines for oxide formation lie below those for sulphides, which means that cerium and lanthanum first react with oxygen dissolved in the steel, and then with sulphur (Fig. 2).

The beneficial effect of cerium, due to its high chemical affinity for sulphur and oxygen, is seen in well-deoxidised steel. Cerium oxides have a more negative Gibbs free energy than oxides of manganese, silicon, or aluminium, making them thermodynamically more stable than typical deoxidation products such as Al_2O_3 or SiO_2 . The equilibrium lines for oxide formation lie below those for sulphides, which means that cerium and lanthanum first react with oxygen dissolved in the steel, and then with sulphur. As cerium is consumed during the formation of non-metallic inclusions, its role may shift predominantly to deoxidation and desulphurisation, which reduces its effectiveness as a modifier. At very low Ce concentrations, most cerium reacts to form sulphides, limiting the ability to modify MnS inclusions. With sufficient Mn and S, phases such as Ce_2O_2S , Ce_2S_3 , and MnS may precipitate simultaneously.

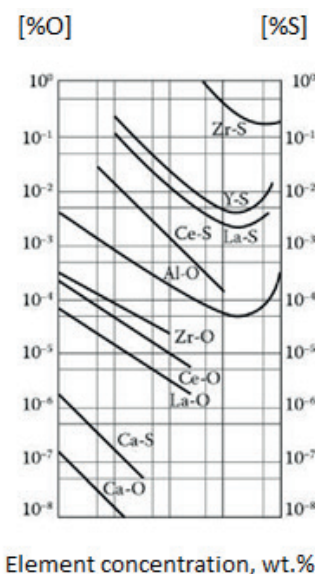


Fig. 2. Equilibrium curves for oxide and sulphide formation at 1,600°C [11]

During aluminium deoxidation, Al_2O_3 forms in the steel, which can react with cerium to produce CeAlO_3 according to Reactions (21) and (14) [14, 19]. The issue of Al_2O_3 inclusion formation as a result of adding Al to steel during refining also applies to the production of high-aluminium TRIP and TWIP steels, where the Al content exceeds 1%, indicating that the contribution of the presented reactions in the transformation of alumina into other forms plays a crucial role. In liquid steel, the formation of non-metallic inclusions such as Ce-P-O and Ce-As-S is also possible, mainly CeP and CeAs. The Gibbs free energy of the formation of these inclusions is higher than that of CeS, Ce_2O_3 , and $\text{Ce}_2\text{O}_2\text{S}$. This means that the occurrence of CeP and CeAs in steel is associated with the segregation of Ce, P, As, and S during solidification and strongly depends on the chemical composition. Their formation limits the unfavourable segregation of P and As at grain boundaries [27].

3. MODIFICATION OF THE CHEMICAL COMPOSITION OF NON-METALLIC INCLUSIONS

The modifying role of cerium is based on reducing and changing existing non-metallic inclusions into complex Ce-containing phases. These modified inclusions become more similar to the steel matrix, so they deform more easily during rolling. Cerium changes Al_2O_3 and MnS inclusions into spherical oxy-sulphide particles, which improves the mechanical properties of the steel. The addition of cerium to liquid steel, MnS and SiO_2 inclusions are transformed into fine $\text{Ce}_2\text{O}_3\cdot\text{SiO}_2$ and $\text{Ce}_2\text{O}_2\text{S}$ particles [6]. A similar effect was also observed for yttrium in alumina inclusions. Research shows that when the amount of cerium increases, MnS inclusions and Al-Si-O systems are converted into phases such as $\text{Ce}_2\text{O}_2\text{S}$, Ce_3S_4 , and CeS. With more cerium, the system becomes dominated by stable Ce-S and Ce-O-S compounds. Yu et al. also reported that after adding Ce, all types of inclusions (MnS, Al_2O_3 , and mixed Al-Si-Ca-O inclusions) eventually transform into CeS and CeO + S phases and the evolution path of Al_2O_3 inclusions follows the sequence: $\text{Al}_2\text{O}_3 \rightarrow \text{CeAlO}_3 \rightarrow \text{Ce}_2\text{O}_2\text{S} \rightarrow \text{Ce}_2\text{O}_2\text{S} + \text{CeS}$. They also identified the presence of the $\text{CeAl}_{11}\text{O}_{18}$ phase in austenitic stainless steel after cerium addition and the CeAlO_3 phase [28].

Calcium is a typical modifier of Al_2O_3 inclusions; however, CaS is formed due to its high chemical affinity for oxygen and sulphur. This phase has a detrimental effect on the steel's properties, as it promotes pitting corrosion of products. Therefore, the degree of calcium treatment must be carefully controlled. In systems containing inclusions of $\text{CaO}\cdot\text{Al}_2\text{O}_3$, reactions with cerium may proceed as described in Reactions (5), (17), (24):



The addition of Ce leads to the modification of $\text{CaS}\cdot\text{C}_{12}\text{A}_7$ inclusions into $\text{C}_{12}\text{A}_7\cdot\text{Ce}_2\text{O}_2\text{S}$. Due to the preferential formation of $\text{Ce}_2\text{O}_2\text{S}$ inclusions, the dissolved sulphur becomes insufficient to react with calcium to form CaS, resulting in the elimination of CaS inclusions. The evolution path of calcium aluminates follows the sequence $\text{CA}_6\text{-CA}_2\text{-C}_{12}\text{A}_7$. Inclusions such as $\text{Ce}_2\text{O}_2\text{S}$ form most easily, and the effect of the modification caused by the cerium addition is significant.

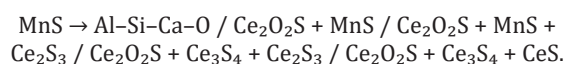
Since cerium is often added in the form of alloys, such as mischmetal, other rare earth metals (REM) also participate in the transformation process. In this case, Al_2O_3 inclusions can transform into more complex phases such as $(\text{Ce,RE})_2\text{O}_3$, $(\text{Ce,RE})_2\text{O}_2\text{S}$, and $(\text{Ce,La})_2\text{O}_2\text{S}$. In aluminium-deoxidised steel, the CeAlO_3 phase forms first and then gradually transforms into Ce_2O_3 and $\text{Ce}_2\text{O}_2\text{S}$.

In steel, inclusions of the $\text{MgO}\cdot\text{Al}_2\text{O}_3$ type also occur. These spinels can likewise be modified by cerium, and the modification path is as follows [28]:

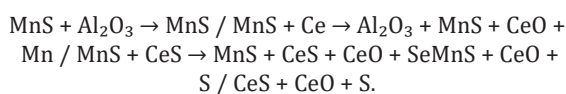


Cerium also modifies MnS inclusions, and this process strongly depends on the contents of O, S, and Ce in the steel. As these elements are gradually consumed and the chemical composition becomes more uniform, sulphur mainly reacts with cerium to form Ce_2S_3 . At the same time, manganese present in the steel combines with the remaining sulphur, which leads to the formation of spherical complex inclusions such as $\text{Ce}_2\text{O}_2\text{S} + \text{Ce}_2\text{S}_3 + \text{MnS}$.

The modification of MnS inclusions in steel was investigated, and the modification process was found to proceed as follows, depending on the Ce content:



Similar results were obtained for pipeline steel. The modification path they proposed is as follows:



MnS modification is also affected by aluminium deoxidation. The Al_2O_3 phase formed earlier can be modified by cerium into CeAlO_3 , and further reactions continue to promote the formation of this phase. This is important for MnS modification because CeAlO_3 particles favour the formation of sulphur-enriched layers around inclusions. As a result, sulphur reacts with cerium to form Ce_2S_3 , while manganese dissolved in the steel can also react with sulphur, which finally leads to the formation of spherical precipitates such as $\text{CeAlO}_3 + \text{Ce}_2\text{S}_3 + \text{MnS}$ [6, 18–19, 29–32].

4. MODIFICATION OF MORPHOLOGY AND SIZE OF NON-METALLIC INCLUSIONS AND STEEL MICROSTRUCTURE

Cerium typically has deoxidising and desulphurising qualities, though it also modifies the grain size. In the case of stainless steel, it improves oxidation resistance. Grain refinement during solidification aims to increase the fraction of equiaxed grains while simultaneously reducing the size of both equiaxed and columnar grains. Depending on the chemical composition of the alloy, steel solidification involves the primary formation of either δ -ferrite (BCC crystal structure) or γ -austenite (FCC crystal structure). During subsequent cooling, δ -ferrite may transform into γ -austenite through a peritectic reaction, whereas the final microstructure can consist of ferrite, pearlite, bainite, or

martensite. Consequently, the solidification pathway and the nature of the phases formed are strongly dependent on the steel grade and chemical composition, implying that different steels require different nucleation substrates and grain-refining mechanisms. Cerium addition results in significant changes in the morphology of the inclusions:

- reduction of their average size,
- transition from irregular to spherical shapes,
- more uniform distribution in the material.

These changes result from the low wettability of cerium inclusions by liquid steel and a high contact angle, promoting their separation and spheroidisation. For instance, inclusions in Ce-modified 55SiCr high-stress spring steel. After adding Ce of 0.02 mass%, the inclusions in the steel mainly consisted of modified MnS, and spherical or ellipsoid Ce–O–S and Ce–S inclusions 1–3 μm in size. However, when the Ce addition was increased to 0.26 mass%, the MnS inclusions disappeared and were replaced by numerous angular and irregular Ce–O and Ce–O–S inclusions over 5 μm in size.

The influence of cerium on the microstructure of steel depends on the steel grade, the type of Ce-based precipitates formed, and the degree of their modification. In most cases, however, its effect is beneficial. In addition to inclusion modification, cerium acts as an effective grain-refining agent. Its addition reduces the size of both equiaxed and columnar grains while increasing the fraction of equiaxed grains, resulting in significant microstructural refinement. Furthermore, cerium suppresses the segregation and precipitation of detrimental elements, thereby improving the mechanical performance of steel.

Microstructural modification and inclusion engineering induced by cerium directly contribute to improved strength, impact toughness, and fatigue resistance of the material. The mechanism of cerium's action is primarily associated with the reduction of stress concentration around non-metallic inclusions and a more homogeneous stress distribution within the steel matrix [29].

Literature data strongly confirm this relationship. The addition of REE reduces the average grain size of austenite in H13 steel from 50 μm to 25 μm , resulting in an increase in impact toughness from 10 J to 19 J. In Nb-microalloyed low-carbon steel a 41.7% reduction in ferrite grain size and a 33.9% decrease in pearlite colony size were observed, accompanied by a 58.7% increase in impact energy. In 2.25Cr–1Mo–0.25V steel the addition of RE elements was reported to lower the bainite transformation start temperature, refine bainitic ferrite, reduce the fraction of carbon-rich martensite–austenite (MA) constituents, and decrease the ductile-to-brittle transition temperature (DBTT). Similarly, the addition of cerium to high-strength aluminium-killed steel reduces the average grain size from 5.06 μm to 2.96 μm and decreases the area fraction of MA constituents from 36.95% to 29.49%. As a result, the absorbed impact energy at -20°C increased from 8.35 J to 19 J [6].

The efficiency of phase nucleation is mainly governed by two factors: a low crystallographic lattice mismatch and a precipitation temperature higher than the steel liquidus temperature. The Ce_2O_3 present acts as nucleation

sites, promoting dendritic refinement and increasing the fraction of equiaxed grains during steel solidification. The addition of rare earth (RE) elements to continuously cast steel (CCS) ingots results in the formation of precipitates with high nucleation potency, which positively influences the ingot microstructure. RE-containing inclusions also improve the impact toughness of cast steel [6]. Cerium is also used in stainless steel to improve oxidation resistance. Its addition reduces the detrimental effect of inclusions by forming stable, spheroidal RE inclusions, thereby improving the mechanical properties of steel. An improvement in the corrosion-resistance of RE-modified stainless steels has also been observed, which is attributed to inclusion modification and the elimination of MnS-type precipitates, thereby reducing the susceptibility to pitting corrosion.

Overall, cerium promotes microstructural refinement, leading to improved mechanical properties, including fatigue strength, weldability, and corrosion resistance. This mechanism is based on heterogeneous nucleation of ferrite or γ -austenite on Ce-containing inclusions such as oxides, sulphides, and oxysulphides. After the addition of cerium to liquid steel, compounds such as Ce_2O_3 , $\text{Ce}_2\text{O}_2\text{S}$, and CeS are formed. Their melting points are higher than the liquidus temperature of steel, allowing them to exist in a solid state during solidification and to act as nucleation sites for new phases. A key factor is the crystallographic lattice mismatch between these particles and ferrite. For Ce_2O_3 , $\text{Ce}_2\text{O}_2\text{S}$, and CeS, it is below 6%, which promotes heterogeneous nucleation. Inclusions such as $\text{Ce}_2\text{O}_2\text{S}$, Ce_2O_3 , CeAlO_3 , Ce_2S_3 , and Ce_3S_4 exhibit lattice misfits below 12% with γ -austenite. Conversely, complex Ce–P and Ce–S inclusions are generally considered detrimental to austenite nucleation. For example, the lattice mismatch of Ce_2S_3 is approximately 1.1%, making it a very effective nucleation site. For CeAlO_3 , it is about 7.7%, indicating moderate effectiveness, whereas for CeP and CeAs, it exceeds 20%, resulting in low nucleation efficiency. The most effective nucleation sites for α - and δ -ferrite are CeS, followed by $\text{Ce}_2\text{O}_2\text{S}$, and then Ce_2O_3 . $\text{Ce}_2\text{O}_2\text{S}$ exhibits the lowest lattice mismatch with α -Fe, making it an effective nucleating agent for α -ferrite. In contrast, the most effective nucleation sites for γ -ferrite are Ce_2O_3 , followed by $\text{Ce}_2\text{O}_2\text{S}$ and CeS. Since α -ferrite is the dominant phase in low-carbon steels, the formation of $\text{Ce}_2\text{O}_2\text{S}$ is crucial for microstructural control. Particles with low lattice mismatch reduce the degree of undercooling required for nucleation. Consequently, the columnar-to-equiaxed transition (CET) occurs earlier, increasing the fraction of equiaxed grains and improving the structural homogeneity. Cerium segregation at dendrite boundaries also restricts grain growth, further refining the microstructure. Moreover, cerium contributes to the elimination of undesirable Widmanstätten structures, which deteriorate the mechanical properties of steel, particularly impacting the toughness [14, 27, 33, 34]. The influence of Ce-containing inclusions on steel performance is also governed by their intrinsic mechanical properties, which may either enhance or deteriorate the overall behaviour of the material. For

example, CeAlO_3 exhibits a higher Vickers hardness and a lower Poisson's ratio than the ferritic matrix, classifying it as a relatively brittle inclusion. However, its coefficient of thermal expansion closely matches that of the surrounding matrix, thereby reducing stress concentration at the inclusion–matrix interface. In contrast, Ce_2O_3 possesses elastic modulus, hardness, and thermal expansion characteristics similar to those of the ferritic matrix, allowing it to behave as a relatively ductile inclusion. $\text{Ce}_2\text{O}_2\text{S}$ exhibits a hardness comparable to that of the matrix and a slightly lower Poisson's ratio; however, its significantly higher coefficient of thermal expansion may promote the development of interfacial stresses during thermal exposure at elevated temperatures [35, 36].

Consequently, doping steel with Ce leads to:

- a reduction in the fraction of columnar grains or their replacement by equiaxed grains in cast steels;
- a similar grain refinement mechanism in ferritic, austenitic, and structural steels, although with variations in intensity;
- a mechanism based on heterogeneous nucleation.

As a result of this process:

- the average grain size is significantly reduced;
- microsegregation of alloying elements is suppressed;
- microstructural homogeneity is improved.

From the perspective of improving the mechanical properties of steel, the formation of an acicular ferrite (AF) microstructure, particularly intragranular acicular ferrite (IAF), is highly desirable. Its randomly oriented interlocking ferrite plates means acicular ferrite not only refines the microstructure and impedes crack propagation but also provides an excellent combination of strength and toughness. Previous studies have demonstrated that inclusions with sizes ranging from approximately $4\text{ }\mu\text{m}$ to $7\text{ }\mu\text{m}$ can act as effective heterogeneous nucleation sites for acicular ferrite formation. The nucleation of acicular ferrite is primarily controlled by the prior austenite grain size and by the characteristics of non-metallic inclusions, including their composition, size, morphology, and population density. Therefore, the deliberate control of inclusion engineering is considered a key strategy for promoting acicular ferrite formation and enhancing room-temperature mechanical properties. In particular, Ce_2O_3 , owing to its low lattice misfit with ferrite, can serve as an effective nucleation substrate for intragranular acicular ferrite during rapid cooling [37].

5. CONCLUSIONS

The role of cerium in modifying non-metallic inclusions, microstructure and properties of steel is determined by its chemical affinity for oxygen and sulphur, as well as by the applied metallurgical and processing conditions. The key effects, benefits, and limitations associated with cerium addition can be summarized as follows:

1. Cerium as an effective inclusion modifier. Cerium exhibits high chemical reactivity towards oxygen and sulphur, enabling effective transformation of non-metallic inclusions (e.g., Al_2O_3 , MnS) into more stable phases such as $\text{Ce}_2\text{O}_2\text{S}$ and CeS.
2. Improvement of mechanical properties. Cerium causes the modification of on metallic precipitates. Inclusion modification leads to a more spherical shape and finer size distribution, reducing stress concentration and improving fatigue resistance, toughness, and overall strength of steel.
3. Influence on microstructure. Cerium promotes grain refinement and increases the fraction of equiaxed grains by acting as nucleation sites, resulting in a more homogeneous steel structure.
4. Optimal cerium content. The most beneficial effects are achieved at cerium contents of approximately 0.01–0.02 wt.%, while higher additions may deteriorate material properties and lead to the formation of unfavourable inclusions.
5. Importance of processing conditions. The effectiveness of cerium depends strongly on the steel composition (especially the O/S ratio), deoxidation practice, and solidification conditions, requiring precise metallurgical control.
6. Limitations of cerium addition. Excessive reactivity of cerium may cause technological issues such as inclusion segregation or clogging during casting.
7. Effect on corrosion and SSC resistance. Modification and reduction of MnS-type inclusions improve corrosion resistance and sulphide stress cracking (SSC) resistance, particularly in aggressive service environments.

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