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Editorial: Inclusion/Precipitate Engineering and Thermo-Physical Properties in Liquid Steels and Alloys

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Editorial on the Research Topic

Inclusion/Precipitate Engineering and Thermo-Physical Properties in Liquid Steels and Alloys

Non-metallic inclusion and precipitate behaviors in the liquid- and solid-state steels and alloys play a significant influence on both the cleanliness and the mechanical and corrosion properties of the materials. Two classical terminologies regarding the control of non-metallic inclusion behaviors exist, "Clean Steel Technology" refers to the investigation of inclusion motion, agglomeration, and its removal from the liquid steel and slag (Mu et al., 2018; Park and Zhang, 2020; Michelic and Bernhard, 2022). When the inclusion size is too small (normally sub-micron size) to remove, "Oxide Metallurgy" provides a suitable solution to utilize these types of specific inclusions/precipitates to refine the prior austenite grain size (PAGS) and induce intragranular acicular ferrite (IAF) formation to improve the steel mechanical property, e.g., low-temperature toughness (Sarma et al., 2009; Mu et al., 2017). Recently, with the development of simulation and characterization methodologies, the boundary of these two concepts starts to overlap, and it is better to use one concept, i.e., "Inclusion/Precipitate Engineering" to describe the correlation of processing, structure, and property regarding the particle behaviors. Very recently, this concept has been applied not only in steels but also in e.g., Ni/Co-based super-alloys (Yang et al., 2021), high entropy alloys, etc. (Wang et al., 2021). Besides the behaviors of inclusions in the steelmaking and casting process, control of inclusions in the state-of-the-art processes, e.g., additive manufacturing (AM) (Eo et al., 2022) is also included in this concept. Last but not least, machine learning (ML) based methods, as well as automatic analysis (Tang et al., 2017), start to be applied in this field extensively to classify different inclusion types and analyze the statistical features rapidly. The schematic illustration of the "Inclusion/Precipitate Engineering" concept is presented in **Figure 1**.

The Research Topic *Inclusion/precipitate engineering and its thermo-physical property in liquid steels and alloys* aims at collecting the state-of-the-art research activities focusing on the experimental and theoretical studies of inclusions and precipitates behaviors, seven peer-reviewed original research articles are collected, covering the topics of inclusion agglomeration in the liquid steels, oxide metallurgy, precipitation in TRIP steel, inclusion classification by machine learning (ML), the thermal conductivity of silicate glasses and melts, precipitation behavior of Fe_2O_3, etc.

Ferreira et al. investigated the liquid inclusion collision and agglomeration in Ca-treated Al-killed steel, the lab-scale experiments found that the liquid calcium aluminates have a tendency to agglomerate and grow. They also reported that the growth is fast immediately following calcium treatment, and subsequently slows down, which may not be found easily in the industrial scale analysis. Finally, they apply the Monte Carlo (MC) simulations to explain the experimental

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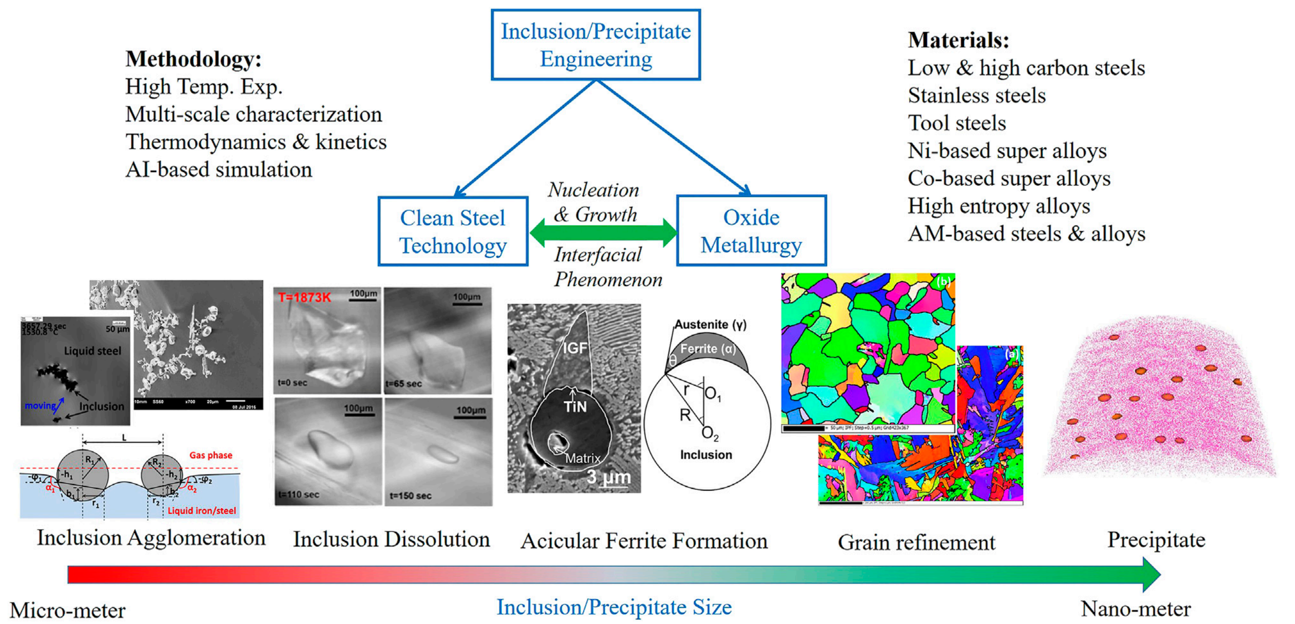

FIGURE 1 | Illustration of "Inclusion/Precipitate Engineering" concept.

phenomenon, and a broad agreement could provide the fact that liquid inclusions agglomeration under laboratory conditions is controlled by laminar collision and Stokes motion. Raviraj et al. provided a robust characterization technique to investigate the reaction between silica in the inclusion and Al in the steel, utilizing the combination of high-temperature confocal laser scanning microscope, X-ray computed tomography and scanning electron microscope (SEM). Utilizing this comprehensive technique, the chemical reaction rate-controlling step could be identified as Al mass transfer. Also, the occurrence of spontaneous emulsification where the mould powder inclusion breaks apart into several small pieces of fragments could be detected. Abdulsalam et al. proposed an ML-based method to predict inclusion type from backscattered electron (BSE) images taken from SEM. The accuracy of two algorithms, i.e., Random Forest (RF) and convolutional neural network (CNN) were evaluated. It is seen that CNN could achieve a better accuracy for the binary (inclusion/non-inclusion) and 4-class (oxides/sulfides/oxy-sulfides/non-inclusion) models. Both CNN and RF could provide a similar accuracy of 60% in the 5-class model which classifies alumina, calcium aluminates, calcium sulfides, calcium-manganese sulfides, and oxy-sulfides. Liu et al. investigated the effect of welding heat input conditions on the microstructure and impact toughness of coarse grain heat-affected zone (CGHAZ) in offshore engineering steel. It is concluded that the HAZ toughness decreases rapidly however the micro-hardness decreases steadily with the increasing heat input from 50 to 100 kJ/cm. Besides the mechanical properties, the heat input has a clear influence on the morphology of each microstructure. With the increasing heat input, PAGS and the width of bainite lath are increased clearly, the fraction of lath bainite decreases while the granular bainite increases. The geometry of M-A constituents also increases but the fraction firstly increases then decreases. This fraction as well as the morphology change of M-A constituents could lead to the fracture mechanism changes from ductile to quasi-cleavage and finally cleavage mode which is deleterious to the mechanical property. NguyenVan et al. studied the precipitation behavior of AlN in Mn-TRIP steel (Fe-0.5%Al-2%Mn) under continuous unidirectional solidification. Experimental results show that both individual AlN and complex Al_2O_3-AlN particles exist in the alloys. Furthermore, the thermodynamic study indicates that Al_2O_3 starts to form at the beginning of the solidification process, while AlN precipitates when Al and N contents exceed the equilibrium value and grow until the end of the solidification. It is also revealed that AlN precipitation could be inhibited by controlling the initial content of N in the melt to less than 0.0072%. Lv et al. provided a parametric study on the pyrolysis conditions on the precipitation behavior of Fe_2O_3 particles, both the physical experiments and the numerical simulations were performed. It is seen that the Fe_2O_3 precipitates with higher purity and concentration and better crystallinity could be obtained by an optimal condition considering the joint influence of temperature, the ratio of $FeCl_2/FeCl_3$ in the pickling liquid, and the added proportion of citric acid. Besides the inclusion and precipitate research, the thermo-physical property analysis is also included in this Theme Collection. Sukenaga et al. conducted the thermal conductivity analysis of sodium silicate glasses and melts. Two vibration models were utilized to understand the mechanism of heat conduction. They conclude that the propagative vibration mode is dominant in the heat conduction process of silicate glasses and melts, compared with borate glasses. However, the diffusive vibration mode is not dominant in silicate non-crystalline materials.

We hope that the collected papers on the present Research Topic could stimulate new insights into the continuation research of "Inclusion and Precipitation Engineering" in advanced steels and alloys, benefiting both academia and industrial communities.

AUTHOR CONTRIBUTIONS

All authors listed have made a substantial, direct, and intellectual contribution to the work, and approved it for publication.

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REFERENCES

Eo, D.-R., Chung, S.-G., Yang, J., Jung, I.-H., and Cho, J.-W. (2022). Numerical Modeling of Oxide Particle Evolution during Additive Manufacturing. *Addit. Manuf.* 51, 102631. doi:10.1016/j.addma.2022.102631

Michelic, S. K., and Bernhard, C. (2022). Significance of Nonmetallic Inclusions for the Clogging Phenomenon in Continuous Casting of Steel--A Review. *steel Res. int.* 93, 2200086. doi:10.1002/srin.202200086

Mu, W., Dogan, N., and Coley, K. S. (2018). *In Situ* observations of Agglomeration of Non-metallic Inclusions at steel/Ar and Steel/slag Interfaces by High-Temperature Confocal Laser Scanning Microscope: a Review. *JOM* 70, 1199–1209. doi:10.1007/s11837-018-2893-1

Mu, W., Jönsson, P. G., and Nakajima, K. (2017). Recent Aspects on the Effect of Inclusion Characteristics on the Intragranular Ferrite Formation in Low Alloy Steels: A Review. *High. Temp. Mater Process* 36, 309–325. doi:10.1515/htmp-2016-0175

Park, J. H., and Zhang, L. (2020). Kinetic Modeling of Nonmetallic Inclusions Behavior in Molten Steel: A Review. *Metall. Mater Trans. B* 51, 2453–2482. doi:10.1007/s11663-020-01954-1

Sarma, D. S., Karasev, A. V., and Jönsson, P. G. (2009). On the Role of Non-metallic Inclusions in the Nucleation of Acicular Ferrite in Steels. *ISIJ Int.* 49, 1063–1074. doi:10.2355/isijinternational.49.1063

Tang, D., Ferreira, M. E., and Pistorius, P. C. (2017). Automated Inclusion Microanalysis in Steel by Computer-Based Scanning Electron Microscopy: Accelerating Voltage, Backscattered Electron Image Quality, and Analysis Time. *Microsc. Microanal.* 23, 1082–1090. doi:10.1017/s1431927617012648

Wang, W., Wang, Y., Mu, W., Park, J. H., Kong, H., Sukenaga, S., et al. (2021). Inclusion Engineering in Co-based Duplex Entropic Alloys. *Mater. Des.* 210, 110097. doi:10.1016/j.matdes.2021.110097

Yang, S.-f., Yang, S.-l., Qu, J.-l., Du, J.-h., Gu, Y., Zhao, P., et al. (2021). Inclusions in Wrought Superalloys: a Review. *J. Iron Steel Res. Int.* 28, 921–937. doi:10.1007/s42243-021-00617-y

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