Lecture 28: inclusion sources and control

Why inclusion control is necessary

Sources of inclusion formation

Control of inclusions

Key words: Inclusion in steel, inclusion engineering, clean steel

Why inclusion control is necessary?

Impact properties are adversely affected with an increase in volume fraction of inclusion as well as inclusion length; spherical inclusions are better. Brittle inclusions or inclusions that have low bond strength with the matrix break up during early straining and create voids at the inclusion/ matrix interface.

Hot fatigue strength of high strength steel is reduced by surface and subsurface inclusions those have lower expansion coefficient than steel

The hot workability of steel is affected by the low deformability of inclusions

Anisotropy of a property is caused by orientation of elongated inclusions along the direction of working. Macro inclusions of sulphides are desirable for better steel machining properties.

In view of the above, control of inclusion in steel is necessary. It must be mentioned and as pointed out earlier (see A. iv), macro- inclusions are harmful and they must be controlled.

Sources of inclusion formation

Inclusions can form either **(**a**)** during transfer of molten steel from one reactor to other or **(b)** during solidification of steel (lecture 27) or during solid state processing by any of the following mechanisms:

i. Reaction between rejected solute elements during solidification, for example, reaction between sulphur and manganese, and between oxygen and aluminium etc.

ii. Mechanical and chemical erosion of refractory and other materials.

iii. Oxygen pickup by teeming stream and consequent oxide formation.

iv. Chemical reactions.

Inclusions produced by mechanism (**i)** are called endogenous, whereas mechanisms **ii** and **iii** produce exogenous inclusions. Inclusions can form during

a) Tapping of molten stream from BOF/EAF to ladle. Erosion of launder refractory is the possible source. Pick up of oxygen from atmosphere and formation of FeO.

b) Treatment of steel in ladle. Here molten steel is in contact with the refractory. Also during deoxidation and synthetic slag treatment oxide/sulphide inclusions may form

c) Teeming of molten stream. Molten steel is in contact with stopper and nozzle refractory and elements like Ti, Mg etc., which can form oxides. Air entrainment into molten steel stream brings oxygen and FeO formation is initiated.

d) Solidification in mould due to precipitation of excess solute elements.

e) Final finishing operations like heat treatment and deformation processing. Here steel is heated to high temperature which may cause surface oxidation, surface sulphurization, inner oxidation,etc.

f) Fusion welding. Oxidation of weld pool, electrode coatings are the possible source of inclusions in fusion welding processes.

Control of inclusions

Inclusions can be controlled either at **(a)** during liquid steel processing stage or **(b)** during solid state processing.

Liquid state processing

During liquid state processing inclusion control can be exercised at tapping and teeming of steel.

i. During tapping of molten stream from BOF/EAF carry- over of slag must be minimized if not prevented. BOF slags are highly oxidizing in nature and contain oxides like $\mathrm{FeO}, \mathrm{MnO}, \mathrm{SiO_2}$, CaO, MgO etc. These oxides react with Al during ladle treatment and lead to inclusion formation. Consider the reaction

$$3\ \mathrm{FeO(l)} +\ 2\ \mathrm{Al} = \mathrm{Al_2O_3} + 3\ \mathrm{Fe}$$

$$3\ \mathrm{MnO(l)} +\ 2\ \mathrm{Al} = \mathrm{Al_2O_3} + 3\ \mathrm{Mn}$$

Carry over of 1 kg FeO in slag decreases Al by 0.286 kg. which in turn forms 0.51kg $\mathrm{Al_2O_3}$. Assuming spherical shape inclusion of 1mm dia (in practice different diameter of inclusions can form) and density of $\mathrm{Al_2O_3} = 4000\,\frac{\mathrm{kg}}{\mathrm{m^3}}$, number of inclusions are 240/kg carry-over FeO of slag. Thus carry-over of slag must be minimized by adopting slag free tapping technologies.

Another way for inclusion formations is reoxidation of tapping stream. Tapping stream exposes very large surface area in the atmosphere and hence oxygen pick up leads to oxide inclusion formation.

ii. Molten steel stream after treatment in the ladle is teemed into tundish and then from tundish to mould in the continuous casting.

Teeming of steel form ladle to tundish requires shrouding of molten steel stream in order to avoid reoxidation. Here macro-inclusions rich in FeO and MnO can form. Moreover, dissolved oxygen increases and forms inclusion during solidification. Use of shrouded and submerged nozzles will help control inclusion formation. Different technologies for shrouding molten stream are: refractory tube shroud, circular ring shroud, etc. The interested reader may see the references at the end.

Teeming of molten steel from tundish to continuous casting mould needs extra precaution in terms of protection of steel against atmosphere. Since oxygen pick up occurs just before the solidification, resulting inclusions do not get sufficient time for separation owing to faster solidification in mold Teeming stream by inert gas or through the use of nozzles submerged in molten stream are the effective means to avoid inclusion formation.

iii. Selection of tundish flux

   Tundish flux should be selected such that it can easily absorb inclusions floating in the tundish .At the same time flux should also cover molten steel to prevent oxidation.

iv. Tundish operation

   Now a days sequence casting is commonly adopted in continuous casting. During ladle change- over tundish feeds the molten steel to different molds of the continuous casting machine. In this situation care must be exercised to ovoid slag entrainment into mold due to vortex formation. Tundish should not be emptied completely. Also tundish lining material should be inert with Al

v. Inclusion can also form in the mold during solidification. As the steel solidifies the excess solute elements like oxygen, sulphur, manganese etc are rejected and lead to inclusions formation.

Segregation during solidification must be avoided. Here stirring of molten steel is effective to minimize the segregation and inclusion formation

Solid state processing

In the solid state processing steel is heated to a temperature ranging in between $800-1200°C$ to perform heat treatment and hot working. Here steel must be heated under inert atmosphere to avoid oxidation. During fusion welding, liquid pool is in contact with air and steel is prone to oxidation. Inert shielding may avoid the inclusion formation.

References:

A.Ghosh: secondary steelmaking

R. Kiessling an N. Lange: Non metallic inclusions in steel.