High Temperature Erosion of Pig Casting Machine Mould

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Abstract— The purpose of this analysis was to find the reason for High temperature Erosion of Pig Casting machine mould in a Ferro alloy industry and to extend its life. The case study was done in Sarda Metals and Alloys Limited, Visakhapatnam, Andhrapradesh. The mould sample was initially tested by optical microscopy; its microstructure was analyzed to study the influence of microstructure to enhance erosion resistance. Hardness was taken by Rockwell Hardness testing machine and its effect was studied to increase erosion resistance. Elemental analysis was also done for new and rejected mould sample to study the effect of alloying elements in High temperature erosion resistance. Current operating condition was monitored and was compared with standard operating condition to remove some bottlenecks. Mould Temperature was measured at every point during operation and found that mould temperature was increased above 500˚C at discharge point, which is one of the reasons for damage of the mould. New refractory coating was proposed in place of old lime coating for moulds to increase mould life, reduce fine generation and good cast quality. Design changes for moulds were suggested to increase the life of mould.

Key words: Mould, Pig Casting Machine

I. Introduction

Metallic moulds are used in Pig casting machine for casting ferroalloys. These moulds can be used as a single slab or multi cavity mould depends upon the size of ferroalloy required. The life of mould depends upon the pouring metal temperature, mould material, mould configuration and operating condition. Mould has a thickness of 63 mm and having weight of 155 kg. Capacity of mould is 5 litres. Total 293 moulds are there in Pig Casting Machine.

Fig. 1: Pig casting machine mould

A. Mould Erosion

The term mould erosion refers to the erosive (abrasive) wear of permanent metal moulds. Erosive mould wear means the continued material loss at the mould surface due to contact and relative movement between the mould surface and incoming melt. In addition to thermal damage to the mould, local surface abrasion of moulds also plays an important role for service life. The highest stresses mainly occur which are in direct contact with the flowing melt resulting in increasing surface roughness. These tribological stresses on the mould are due to abrasive effect of silicon contained in Silicomanganese alloys and of oxides and intermetallic phases. The resulting damage to the mould surface is called erosion. Main factors responsible for mould erosion are Geometry, Velocity and angle of impact of melt onto the mould during the mould filling process, Time of exposure to wear stresses, Maximum temperature and time and site related temperature pattern or gradient. Turbulance and cavitation also promotes wear and should be avoided. Adhesion, Soldering, Corrosion and warm cracks increase with a rising mould temperature. Erosion on the other hand depends on viscosity or the fraction of melt which has already changed to pasty state. In recent years studies have shown that the main cause for erosion can be induced by solid particles in the melt. This particularly refers to pre-solidified silicon particles, but also to oxides and intermetallic phases which results in increased abrasive wear of the mould surface.

B. Erosion Theory

The most important theory for understanding impact erosion caused by liquid metal drops is that of guided acoustic shock (GAS). This theory explains the impact of high velocity liquid drop on a plane surface based on two effects. 1.) Direct influence of impact pressure on the mould surface. 2.) Subsequent near surface washout in transverse direction.

If impact event is considered as a one dimensional problem and solid as a rigid, the pressure produced at the point of impact is given by water hammer pressure.

$$P = \rho c v \quad \text{(for cylindrical jet)}$$

$$P = \frac{1}{2} \alpha \rho c v \quad \text{(For spherical drop)}$$

ρ = Density
c = Acoustic velocity of liquid
v = Impact velocity

Pure nickel is more erosion resistant than Al 7075-T6 may be attributed to higher ductility due to relative lack of dislocation barriers in the single phase metal. In normalized mild steel carbon was found to enhance erosion resistance only upto concentration of 0.4%. On the other hand, the same steel in the martensitic state exhibited a continuous increase in erosion with increasing carbon content to greater than 0.8%. These differences were attributed to brittle nature of cementite in the normalized high carbon alloys, the formation of which is suppressed during martensitic transformation.

C. Prediction of Erosion Resistance

In order to able to predict the response of a material to liquid impact, considerable effort has been expanded in attempts to correlate erosion resistance with bulk mechanical properties.

The properties most commonly considered are Tensile strength, Ductility, Hardness, Impact Resistance, Strain Energy, Ultimate Resilence, Fracture Toughness and Fatigue limit.

D. Materials for Moulds

PCM machine moulds are generally used of ferrous alloys, because of its availability and cost we can enhance their properties by adding some alloying elements for high temperature application. Different steel grades are available but our concern is to select a material which can sustain their properties like erosion resistance, creep strength, hardness, Corrosion resistance etc at high temperature. These are different types of steel given below.

E. Low Carbon Steel:

Contain less than about 0.25 wt% carbon, Relatively Soft and Weak, Outstanding ductility (25% EL) and Toughness, High machinability and Weldability, Least expensive to produce, Tensile Strength (415- 550 Mpa).

F. Low Alloy Steel:

Contain alloys such as Cu,V,Ni & Mo up to 10 wt %., High strength and corrosion resistance than plain low carbon steel, Tensile strength up to 700 Mpa, .Main Applications are Beams, Channels, nuts, bolts, Wires, Tin cans etc.

G. Effect of Alloying Elements on Steel

S.No.	Alloying Elements	Properties
1	Boron	Improves hardenability without loss of machinability
2	Chromium	Improves oxidation and corrosion resistance at high temperature, Promotes ferritic microstructure. Corrosion resistance may also be enhanced by Ni and Mo additions
3	Cobalt and Tungsten	Improves strength and hardness at elevated temperature
4	Sulphur	Improves machinability when combined with manganese. Alone it increases brittleness and lowers impact strength and ductility
5	Manganese	Improves hardenability and wear resistance. Counteracts the brittleness caused by Sulphur. Improve hot ductility. At low temperature manganese is an austenite stabilizer, but at high temperature it will stabilize ferrite. Manganese as an austenite former, can also replace some of nickel in stainless steel.
6	Molybdenum	Improves hardenability, Toughness, Improves elevated temperature strength, Creep resistance. Promotes a ferritic microstructure. Increase resistance to both uniform and localized corrosion. It also enhances the risk for the formation of secondary phase in ferritic, duplex and austenitic steels. In martensitic steels it increase the hardness at higher tempering temperature due to its effect on carbide precipitation.
7	Nickel	Increase strength and hardness without sacrificing ductility and Toughness. Promote an austenitic microstructure. Reduces corrosion rate in active state i.e advantageous in acidic environment.In precipitation hardening steels nickel is also used to form intermetallic compounds that are used to increase strength. In martensitic grades adding nickel, combined with reducing carbon content, improves weldability
8	Vanadium	Increase strength, Hardness, Wear resistance and Resistance to shock impact at high temperature
9	Titanium	Improves strength and Deoxidizes steel. Titanium is a strong ferrite and carbide former, Lowering the effective carbon content and promoting a ferritic structure in two ways. In austenitic steels with increased carbon content it is added to increase the resistance to intergranular corrosion(stabilized grades), but it also increases mechanical properties at high temperature. In ferritic grades titanium is added to improve toughness, Formability and corrosion resistance. In martensitic steels titanium lowers the martensite hardness by combining with carbon and increases tempering resistance. In precipitation hardening steels, Titanium is used to form the intermetallic compounds that are used to increase strength.
10	Carbon	Carbon is a strong austenite former that also significantly increases mechanical strength. In ferritic grades carbon strongly reduces both toughness and corrosion resistance. In martensitic grades carbon increses hardness and strength.
11	Silicon	Silicon increase resistance to oxidation, both at high temperatures and in strongly oxidizing solutions at lower temperatures. It promotes a ferritic microstructure and increases strength.
12	Copper	Copper enhances corrosion resistance to certain acids and promotes a austenitic microstructure. It can also be added to decrease work hardening in grades designed for improve machinability. It may also be added to improve formability.

H. Effect of Temperature

- High temperature accelerate corrosion process. The result is that certain gases or liquids which are considered innocuous under ambient conditions become aggressive to materials when hot.
- Most common process temperatures are in the range 450◦C to 850◦C or higher. Materials of construction must withstand excessive metal loss by scale formation from oxidation and from penetration by internal oxidation products that could reduce the remaining cross sectional area to a level that cannot sustain the load bearing requirements. The component will then yield and may swell or distort.
- Most high temperature reactions involve oxidation process. In part this is because oxides are common products of reaction in many application where air or oxygen rich environments pertain.
- The Scaling temperature for carbon steel is about 550°C, which reflects the temperature where iron produces Wustite (FeO). Wustite Contains many ionic defects that permit rapid transport of reactant species and hence more extensive scaling with associated metal wastage

I. Alloy Degradation at High Temperature

- Most high temperature materials exhibit metallurgical changes following long term use. In some cases there is a local grain boundary melting ("burning") as a result of gross overheating.
- Phases form at the expense of other elements, such as loss of chromium by carbide formation during sensitization of austenitic steels in the range of 510
- To 788◦C, which renders the steel less resistant to aqueous corrosion?
- Sustained heating of ferrites or cast austenitic stainless steel between 650 and 870◦C can lead to carbide precipitation and sigma phase formation. Both carbide and sigma phases result in a loss of ductility.

II. EXPERIMENTATION & OBSERVATION

Mould sample was tested by optical microscopy to analyze its microstructure. Hardness testing was done through Rockwell hardness testing machine. Elemental analysis was done by atomic emission spectroscopy and its elemental composition was analyzed. During operation of Pig casting machine, mould temperature was measured at every point using Pyrometer.

III. RESULT & DISCUSSION

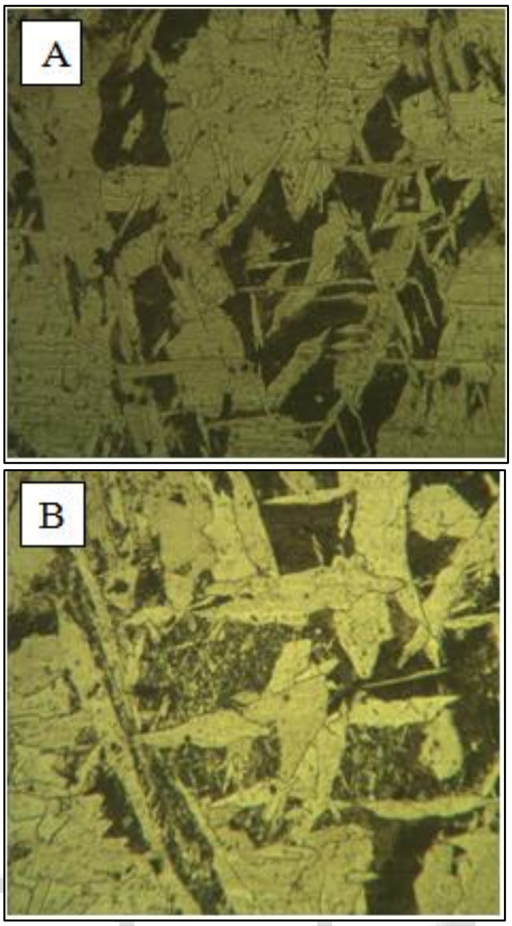

Fig. 2: Optical micrograph of mould sample of steel grade IS 3038 at (A) 100X magnification (B) 200X magnification

A. Influence of microstructure on Erosion Resistance

- Increased pearlite share in the structure of low alloyed steel has a positive effect on their erosion resistance.
- The growing share of carbides or other hard phases has a predominant advantageous effect on erosion resistance. Carbides act as a obstacles against the penetration of erosive particles.
- The lowest erosion resistance at low impact angles occurs in low-carbon steel with ferritic structures, with the growing share of pearlite in the structure,erosion resistance increases.
- Strong carbide forming elements such as chromium, molybdenum and vanadium retard the rate of softening during tempering.
- In the Fe-C-Cr and Fe-C-Mo systems, their pearlite growth is retarded because Cr and Mo atoms must diffuse, a process that is much more sluggish than the diffusion of carbon because of much larger size of alloying elements.
- Depending on the percentage of carbon of the steel, then it is possible to have a microstructures consisting of 100% ferrite (if carbon content is less than or equal to 0.02%) or 100 % pearlite (If the carbon content is equal to 0.77%).

Hardness was taken by Rockwell hardness testing machine of low alloy steel mould sample of grade IS 3038. Minor load 10 kg with 1/16 inch diameter steel ball indenter. Results shown belowTable-1

S.No.	Rockwell Hardness (HRB) Scale	Average Hardness
1.	83.7	83.8
2.	84.3	
3.	85.2	
4.	85.4	
5.	82.7	
6.	81.5	

Erosion is related to a process of plastic deformation followed by rupture that eventually causes the surface material to break away. The rupture of material in a surface layer is a necessary step for the occurrence of erosion and it happens as the plasticity of material is exhausted. As such, the erosion resistance relies on the hardness (or resistance to plastic deformation) and ductility (maximum plastic deformation allowable) of material. A material displaying good resistance to erosion would possess both high hardness and good ductility. Generally, the ductility of metals is inversely related to hardness. The correlation between erosion resistance and the mechanical properties of material depends on the erosion mechanism. For a material with high hardness and low rupture ductility, the erosion resistance would be insensitive to the change of hardness but would be improved as ductility is improved. For a material with high ductility and low hardness, such as low carbon steel, an increase of hardness can reduce the erosion rate.

B. *Mould Temperature*

Mould temperature varies continuously during pouring operation. This very important factor is responsible for erosion/damage of mould. Some steady state temperature should be maintain to avoid thermal stress cracking (e.g for ferrous mould it should be below 500◦ C). Inner Mould temperature was measured by using a temperature gun (Pyrometer) for current PCM mould operation. Started with empty PCM mould at pouring point as shown below.

Operation	Mould Temperature (◦C)
Before Pouring	94
Water cooling	385
Discharge	395
Lime coating	243
Before Pouring(2nd cycle)	217
Water cooling(bottom)	248
Discharge	380
Lime coating	206
Before Pouring(3rd cycle)	228
Water cooling(Bottom)	322
Discharge	568
Lime coating	283
Before pouring	234

Table 2: Refractory composition

Process was complete in thirty minutes and temperature of mould reaches 568◦C in third cycle as shown in table 2 ,It should be maintained below 500◦C at every point.

C. *Proposed mould design and operating condition*

In the new method of casting ferroalloy, ferroalloy can be casted in a controlled shape for ease in handling and possessing uniform alloy chemistry throughout the individual casting and eliminates the generation of fines. The method and apparatus is for economically producing cast bodies.

1) Providing a moving train of ferrous moulds, each having one or more cavities therein, the mass of each mould being between about 6 to 25 times greater than the mass of the bodies to be cast.
2) Coating the mould cavities with layer of refractory material.
3) Pouring molten ferroalloy or slag into the train of moving mould cavities.
4) Cooling the cast bodies and the moulds by water spraying.
5) Discharging the solidified cast bodies from the moulds while maintaining a steady state temperature in the ferrous moulds below about 500◦ C.

The moulds contain one or more cavities of a preselected dimension and in all cases, the mass of the moulds is at least 6 to 25 times greater than the mass of the ferroalloy. Molten metal is transferred to a pouring launder which has a plurality of nozzles or orifices in its side or bottom in matching, spaced relationship to the transverse array of cavities contained in the moulds. The casting machine also includes a conventional slurry mix tank and spray means positioned on the underside of the moving train of moulds to apply a light coating of refractory material, such as alumina, silica, magnesium oxide, zirconium oxide, and carbon to the empty mould cavities as they pass above the spraying element. The heat remaining in the moulds tends to evaporate the water in the refractory slurry coating, leaving a thin, dry layer of refractory coating in the empty mould cavity.

D. *Proposed Thermal Insulation coating for PCM Mould.*

The present coating creates a thermal barrier to limit the rate of heat transfer into permanent mold and thus contribute to increasing the useful life expectancy of permanent mold. The volume of pinholes and other gas defect formed in casting product caused by blowout gases are reduced or nearly eliminated by moulds having present coating.

The refractory glass employed for coating is an amorphous (non- crystalline) brittle solid and has limited internal porosity and low surface attraction for water relative to existing conventional mold insulating coating composition.

The term glass, as employed in current coating refers to an amorphous (non-crystalline) solid material formed by rapidly quenching a liquid metal oxide or combination of oxides. Such compounds may or may not have a glass transition temperature at some point below the melting point. Glass transition is the transition in an amorphous material having a hard relatively brittle state to a rubbery liquid state. This transition occurs at a temperature lower than the melting temperature of material.

Chemical compound	Percent weight
SiO_2	35-45
Al_2O_3	8-15
CaO	25-35
MgO	7-13
Fe_2O_3	3-7
TiO_2	1-2

IV. Conclusion

From our study on moulds, we considered various factors responsible for mould erosion/damage of Pig casting machine moulds at Sarda Metals and Alloys Limited, Visakhapatnam, A.P. Mould Materials, design and Coating are analyzed and tried to improve all this factors by some advance improved methods.

- Mould temperature should be stabilize below 500◦C to avoid large thermal stress cracking and damage of mould.
- In Pig Casting machine when rail of mould is moving during casting process, Mould temperature fluctuation should not be greater than 150˚C. It affects the life of mould.
- Mould coating should be done with the layer of refractory material.
- For PCM mould, I have studied its current design and found some improvements as shown below.
  1) Mass of each mould should be between 6 to 25 times greater than the mass of bodies to be cast. High production yield and improved mould life are obtained.
  2) This improved designed method virtually eliminates the generation of fines.
  3) A preferred range is about 7 to 15:1 mass ratio.
- New refractory glass coating is proposed for PCM mould having composition contain Silicondioxide, Magnesiumoxide, Calciumoxide, Aluminiumoxide, Titaniumoxide, and Ironoxide mixed in water and form a refractory slurry for mould coating.
- The coating creates a thermal barrier to limit the rate of heat transfer into permanent mould and thus contribute to increasing the useful life expectancy of permanent mould. The volume of pinholes and other gas defect formed in casting caused by blowout gases are reduced or nearly eliminated by moulds having proposed coating method.

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