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A way to use ladle slag to partially replace lime in BOF

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With the requirements of sustainable development and to adopt principles of circular economy in steel industry, slag utilization has become a hot issue. As a consequence, 3R (Reduce, Reuse and Recycle) technique of waste handling has become most popular among the industries. This paper focuses on recycling of Ladle Slag (LS) generated after secondary refining process in BOF. Industrial trials were conducted with varying amount of recycled LS to the BOF at Visakhapatnam Steel Plant (VSP), India. The effect of LS addition on steel refining was also studied by taking intermediate steel and slag samples at different stages of refining namely, 1st, 2nd/middle and end of blow (EOB). It was observed from the trials that LS addition helps in early slag formation due to its low melting point which was confirmed by measuring in Ash Fusion equipment. Basicity and phosphate capacity of slag collected at different stages of refining was compared with and without LS addition. High basicity of slag was observed in the early stages of blow which further confirms that it helps in early slag formation. Phosphate capacity of BOF slag was calculated and found that it was better than without LS addition. Effect of LS addition on the FeO generation in the BOF slag was also studied and it was found that, particularly in first and middle stage of blow FeO generation was higher. However, FeO level was lower in the EOB stage which confirms that it has no negative effect on BOF lining. Finally, it can be concluded that addition of LS in BOF has no negative effect on steel refining and 1t of lime can easily be saved with 2t of LS addition.

KEYWORDS: LADLE SLAG, WASTE UTILIZATION, EARLY SLAG FORMATION, BOF, DEPHOSPHORIZATION;

INTRODUCTION

In most of the countries, iron and steel making industries are now putting remarkable emphasis and thrust on recycling of waste for sustainable development and environmental management [1]. Steelmaking is energy intensive process in which million tons of slag was generated as by-product. Efforts for economical use of steel plant wastes such as slag, dust, and flue gases by recycling not only helpful to reduce the environmental load and also for the conservation of natural resources [2]. During steelmaking, ferroalloys are added to the liquid metal in order to obtain the desired steel grade, and together with some additives like lime and synthetic slag which forms basic slag. Refining of steel for better desulfurization, inclusion absorption and also to fine tune the steel composition before sending to casting from Ladle heating furnace (LHF) is one of the most widely used global refining methods [3]. During this process, considerable volume of ladle slag (LS) is generated annually. The chemical composition of

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ladle slag varies according to type of steel grade produced i.e. Al killed steel/ Si killed steel, grade of steel and also on amount of ferroalloys, aluminium, lime and synthetic slag additions during steel making process.

In LHF, the refining slag usually is of a high basicity and calcium oxide content, which is required for desulfurization during refining. CaO, SiO_2, Al_2O_3, and MgO are main oxides present in the slag, which makes this slag a potential binder in alkali activation [4-7]. Ladle slag is a high-calcium-based alkaline industrial solid waste contains approximately 50% CaO by weight, so it can be used to partially replace lime in a metallurgical process [8]. However due to significant variation in chemical compositions depending on the production process, it may hamper the stability of the metallurgical process in a steel plant. Therefore, for the application described above has not been widely tried by many authors [9]. It is a pre-melted flux with low melting point and its melting characteristics are very much similar to synthetic flux. So, it can also be used as an alternative for ladle flux substitution [10-14].

Unlike BF slag, the utilization of LS is very limited. But it is primarily crystalline in nature due to the high basicity and slow-cooling conditions adopted during cooling after dumping from the casting [15]. The crystalline phases usually observed are dicalcium silicate (γ-C_2S), mayenite ($12CaO.7Al_2O_3$), periclase (MgO) and a trace of gehlenite ($2CaO.Al_2O_3.SiO_2$) [16,17]. LS do not contain any harmful constituent which will affect the environment and it is a mesoporous material with large specific surface area [18, 19]. The low recycling for reuse of LS slag was mainly attributed to its volume instability i.e. disintegration of slag during cooling due to phase transformation and wide-ranging slag composition [20]. The disintegration of LS slag is a long examined problem in the steel-making process, especially while making silicon killed steels this phase transformation causes disintegration of the slag in to a fine powder. There has been quite a bit of studies were reported by various authors and suggested different additives in order to prevent disintegration and stabilization of LS slag [21-23].

RINL/VSP generates around 20 kg ladle slag per tonne of crude steel. With this estimation, more than 1 million tonnes of ladle slag is generated per annum at RINL. RINL generally makes Al/Si killed steel grades which contain low alumina in the range of 8-18% which makes it unsuitable as replacement to synthetic slag. Variation in the chemical composition of ladle slag generated at RINL is also quite less as all generated slag is dumped at common dump yard where it gets mixed and homogenised.

The objective of the present study is to recycle ladle slag in BOF and to evaluate its effect on the process parameters. Few researchers [24-25] studied the effect of ladle slag addition on the lime dissolution rate during early slag formation in BOF. They also reported that ladle slag addition in BOF can reduce lime consumption by 2 kg per tonne of crude. But in this study, lime saving of 7.5 kg per tonne of crude steel was achieved on consistent basis in more than 60 heats (2 tonnes of ladle slag addition replaced 1 tonne of lime). Ladle slag contains high alumina and in literature [26-27], it is mentioned that high alumina hampers dephosphorization. In this study, ladle slag generated during the regular production process in RINL/VSP were recycled for partial replacement of lime in BOF and its effect on dephosphorisation at different stages of blowing were studied. In addition to that effect of ladle slag on the BOF refractory erosion, its cooling effect during blowing along with varying amount of ladle slag addition as a function of Si content in the hot metal is also studied in detail. These parameters were not studied by the previous researchers.

THEORY AND CHARACTERIZATION METHODS

Melting and XRD analysis of ladle slag

Several researchers [24-25] have reported that ladle slag addition in BOF helps in early slag formation due to its low melting point characteristics. Sanghamitra Bharati et al. [13] measured the melting point of ladle slag with Ash fusion equipment and reported that it is less than 1603 K. The slag composition reported in their study is slightly different from the current study as variation in the content of alumina and silica is quite high. Hence, in order to ascertain the melting and softening characteristics of ladle slag used in present study, melting experiments were carried out in Ash fusion equipment (Model: Carbolite GERO CAF G5, heating rate: 8°C/minute, maximum temperature: 1873 K). The chemical analysis of ladle slag is presented in Table 1. Melting range characteristics of ladle slag is presented in Figure 1. Six samples were tested with slight variation in

composition to ascertain the melting temperature range of ladle slag and found to be in the range of 1653-1693 K. From the results it was found that average melting temperature of ladle slag is 1673 K (Hemisphere temperature).
X-ray diffraction analysis was carried out for deeper insight to know the mineralogical constituents present in the ladle slag (Model: Panalytical Empyrean) using Cu Kα source between angle 2θ of 10° and 90° with an increment of 0.02° and is presented in Figure 2. (XRD, Panalytical Empyrean) using Cu Kα source between angle 2θ of 10° and 90° with an increment of 0.02° and is presented in Figure 2. From the results it was observed that major mineralogical phases present in ladle slag are di-silicate calcium (C_2S), periclase (MgO) and Gehlenite.

Tab.1 - Chemical analysis of ladle slag (wt. %).

	CaO	MgO	SiO_2	Al_2O_3	FeO	MnO	P_2O_5	S	Melting range (K)
Ladle Slag	40-48	11-13	18-22	8-18	1-3	1-2	0.2-0.4	0.2-0.3	1653-1693

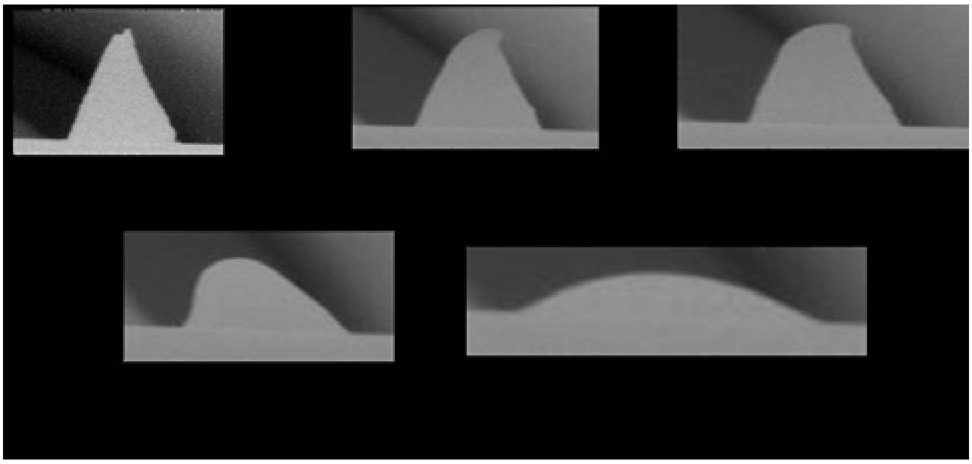

Fig.1 - Melting range determination of ladle slag generated at RINL.

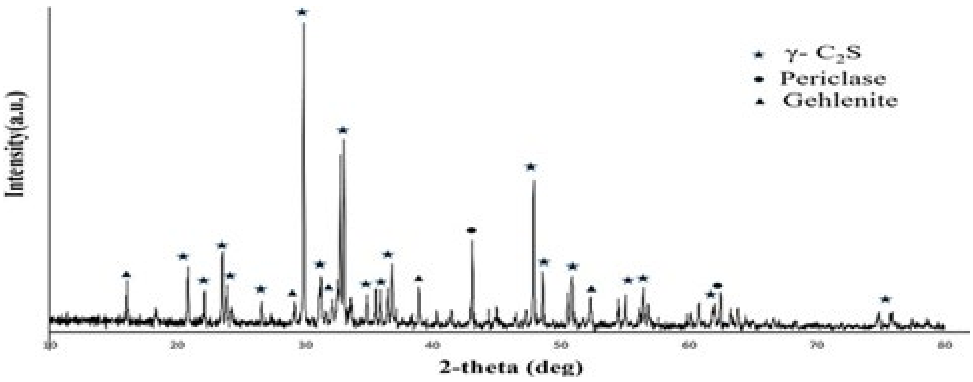

Fig.2 - XRD analysis of ladle slag.

Slag weight estimation

The slag weight calculations are based on the conservation of mass principle for the components Si/SiO_2 in the studied system is presented in Equation (1).
Silicon balance:

$$M_{SL} = [M_{HM}*\%Si_{HM}*(28/60) + M_{SC}*\%Si_{SC}*(28/60) + M_{SF}*\%(SiO_2)_{SF} + M_{CL}*\%(SiO_2)_{CL}]/[(\%SiO_2)_{SL}] \quad \text{(eq.1)}$$

Where subscripts SL, HM, SC, SF and CL denote; slag, hot metal, scrap, slag formers and coolant respectively. $\%Si_{HM}$ and %SiSC is used to donate silicon wt.% in hot metal and scrap respectively. $\%(SiO_2)_{SF}$ and $*\%(SiO_2)_{CL}$ is for silica content (wt.%) in slag formers and coolant respectively. Slag formers used in this study are lime, dolomite and ladle slag while iron ore is used as coolant. Unit of the calculation is in tonnes.

Cooling effect of ladle slag

Dahlin et. al. [24-25] reported that the iron ore consumption is reduced with ladle slag addition due to disturbed heat balance. However, cooling effect of ladle slag was not estimated and compared with iron ore in their study. Quantification of iron ore reduction with ladle slag addition was also not reported. In this study, an attempt was made to approximately estimate the cooling effect of ladle slag through the data available in the literature. S.K. Gupta [28] estimated the cooling effect of iron ore which was based on the two effects: a) Sensible heat of iron ore b) Reduction of FeO/Fe_2O_3. The cooling effect of iron ore is presented in Table 2. He also stated that as iron content of iron ore decreases its cooling
effect decreases due to lesser amount of chemically bonded oxygen. Cooling effect of ladle slag was estimated with the specific heat capacities of slag reported by Wang et. al. [29]. The specific heat capacity of slag is presented in Table 3. Average melting point of ladle slag is taken as 1673 K as per Table 1.

Tab.2 - Cooling effect of iron ore.

Addition	Heat effect (MJ/t)	%Fe	$\%O_2$
Iron ore	4788	70	30

Tab.3 - Specific heat capacity of slag.

Slag	Average specific heat capacity of solid materials	Latent heat of fusion	Average specific heat capacity of liquid materials
Unit	$kJ.kg^{-1}.k^{-1}$	$kJ.Kg^{-1}$	$kJ.kg^{-1}.k^{-1}$
	1.0	209.2	1.247

Cooling effect of ladle slag is estimated approximately 2022.2 MJ/t which is about 0.42 times of iron ore (4788/2022.2=0.42). Cooling effect of ladle slag estimated is just an approximate value but it gives insight to the blowers in real time to maintain thermal balance of BOF vessel with respect to the opening temperature.

Phosphorus partition ratio and phosphate capacity of BOF slag

Yang et al. [30] have described several notations for phosphorus partition ratio, although all have explicit meaning. In this study, partition ratio is described in Equation (2).

$$L_P = \frac{\%P_2O_5}{\%P} \tag{2}$$

LP can easily be calculated from slag and corresponding steel sample compositions taken at different stages of blowing.

The dephosphorizing ability of slag can be calculated by considering its phosphate capacity.

The gas-slag equilibrium reaction in Equation (3) can be used to introduce the phosphate capacity $(C_{PO_4^{3-}})$ which is defined by Wagner et al. [31].

$$[P]+\frac{5}{4}[O]+\frac{3}{2}(O^{2-})=(PO_4^{3-}) \tag{3}$$

$$C_{PO_4^{3-}} = \frac{(\%PO_4^{3-})}{P_{P_2}^{\frac{1}{2}} P_{O_2}^{\frac{5}{4}}} = \frac{K_{PO_4^{3-}} a_{O^{2-}}^{3/2}}{f_{PO_4^{3-}}} \tag{4}$$

where ($\%PO_4^{3-}$) is the mass% of phosphate ions in the slag, $(K_{PO_4^{3-}})$ is the equilibrium constant for formation of reaction given in Equation (3), (P_i) is the partial pressure of species i, (f_i) is the activity coefficient of species I and $(a_{O^{2-}})$ is the activity of in the slag. $(P_{O_2}^{\frac{5}{4}})$ can be estimated with Equation (4). Pathak et al. [32] explained the procedure for the

estimation of phosphate capacity of BOF slag, the same has been adopted in this study.

Experimental Procedure

Plant trials were carried out at RINL/VSP 150 t BOF in Visakhapatnam, India. Ladle slag (LS) derived after secondary refining in ladle refining furnace (LRF) / Argon rinsing station (ARS) is dumped into the container after the casting. Then crushing and classification was carried out y using crushers, magnetic separators and screens to get ladle slag in the desired size range of 10-60 mm and used in the present study to partially replace lime in BOF.

Plant Trials

The campaign of recycling ladle slag was conducted in 80 heats. Out of 80 heats, in 60 heats, 2 t of ladle slag was added per heat while in rest of the heats, 0.5-1.5 t of ladle slag was used.

To comprehend the partial replacement of lime with ladle slag in BOF, in every heat, ladle slag was added at the bottom the convertor after the scarp addition and studied. During trials with ladle slag, soft blowing tendency was observed which was handled by modifying lance profile without changing the oxygen flowrate. Apart from lime replacement, effect of ladle slag addition on refining of steel particularly dephosphorization, was also studied in this study. In this perspective, 16 exclusive industrial trials were carried out in which ladle slag was added in 8 heats while heats were normal heats. Steel and slag samples along with temperature were taken at different stages of refining. The stages at which samples are

collected are given below.

1. Initial phase: blown oxygen ranging from 2,500–3,500 Nm³ (After desiliconisation period).
2. Middle Phase: blown oxygen ranging from 4,600–5,800 Nm³ (During peak decarburization period)

3. End of Blow (EOB): blown oxygen ranging from 7,000–7,500 Nm^3.

In every heat, blowing was stopped twice and the converter was tilted forward to take slag and bath samples along with temperature. Slag samples were collected with the help of the spoon which is used to scoop the slag from the BOF converter while steel samples were taken with a lollipop sampler. The chemical composition of slag was analysed in wavelength dispersive X-ray fluorescence (WDXRF) spectroscopy (Axios mAX, Malvern Panalytical, United Kingdom). The composition of steel samples was done by Thermo Fisher Scientific ARL iSpark 3500 optical emission spectrometer (OES).

RESULTS & DISCUSSION

Early slag formation

Lime dissolution is the most important aspect in BOF refining process. As per literature [33], it is clear that during blowing added lime interacts with slag and heats up with a slag layer on it then it will be solidified around the lime particles. Re-liquefaction of frozen layer and dissolution of lime can only take place after the penetration of molten slag into the pores of lime. This penetration process is intensified if sufficient amount of FeO present in the slag as it reduces the viscosity of BOF slag. Hence, optimum FeO generation is the most important aspect of lime dissolution in the early stage of blow.

In RINL, all the slag formers are added within the 3-4 minutes of the blow to avoid disturbance in the blow dynamics inside BOF. Later addition of slag formers disturbs the gas flow during blowing and hence disturbs the overall blowing process. Lime reactivity is also a concern for RINL as it is varying in the range of 270-300 which is quite low as per the standard reactivity of 350. Thus, at RINL, lime addition during blowing is deliberately kept on the higher side and will be around 10-15 times of the Si content present in the hot metal which is 1 tonne extra that is being calculated with the mass balance model to maintain end of blow slag basicity of 3.5. Lime addition decreases as Si content of hot metal increases. It is generally 15 and 12 times when Si content of hot metal is less than 0.4 and in the range 0.4 to 0.7 respectively beyond that it is 10 times.

It was observed from the intermediate steel and slag sampling for normal heats (without ladle slag addition) particularly at the 1st stage of blow i.e., 2500-3500 Nm^3 of oxygen that FeO level in the slag was low and with average value of 13.3% as shown in Figure 3. This low FeO level in early slag resulted in low basicity which is varying in the range of 1.5-2.2 with average value of 1.8. Outcome of low FeO and basicity in the early stage of blow is reflected in lower dephosphorization efficiency of 20%. Liu et al. [34] reported that dephosphorization efficiency of 44% was achieved in their study particularly in the 1st phase of blow with average basicity of 1.8. This low basicity is understandable in their study as the amount of lime was adjusted for only this stage, after that deslagging was done and another batch of lime was added. However, in this study all lime was added initially which means that lime dissolution was not proper which is reflected as low slag basicity of 1.8. Average bath temperature recorded in this study and the study conducted by the Liu et al. [34] was 1793 K and 1600-1700 K respectively.

The same trial was repeated with 2 tonnes of ladle slag addition and intermediate slag and steel samples were collected after same interval of blow. It was observed that average FeO generation was higher i.e., 15.1% compared to without ladle slag addition which in turn increases the average basicity of the slag to 2.8. High basicity of slag may be attributed to low melting of ladle slag that is 1673 K helps in its easy dissolution along with increasing kinetics of lime dissolution. Maintaining high FeO and basicity helps in achieving high average dephosphorization efficiency of 26% even though lime addition was reduced by 1 tonne with ladle slag addition as presented in Table 4. It was also observed that the slag properties are not affected but rather got improved with ladle slag addition particularly with respect to FeO, basicity and dephosphorization efficiency. Apart from high FeO and basicity of slag, average temperature of bath after 1st stage was lower with ladle slag addition i.e., 1696 K which also helped in achieving high average dephosphorization efficiency. Low opening temperature was mainly due to high cooling effect of ladle slag.

Middle blow period

As per Cicutti et al. [35] and IMPHOS report [36], middle blow period experiences the peak decarburization with sharp decrease in FeO content of the BOF slag. Cicutti et al. [35] conducted trails in 200 t converter and collected samples at different stages of refining and observed that minimum FeO was present in the slag close to the middle period of refining. The same phenomena were observed in the present study for both trials with and without ladle slag addition. High FeO level in the early stage of blow with ladle slag addition was helpful in maintaining good FeO level even in the middle blow. Average FeO level in the middle stage of blow was 14% and 12% for with and without ladle slag addition. Phosphorus reversal in the middle blow was observed in only 2 heats without ladle slag addition which may be due to thick slag formation. Phosphorus reversal was not observed with ladle slag addition. This was possible because of low melting point of ladle slag helped in maintaining good FeO level and low viscosity of refining slag. In few heats (without ladle slag addition), thick slag was observed while taking samples in the middle blow particularly in those heats where FeO level was less than 10%. Thick slag was not observed with ladle slag addition.

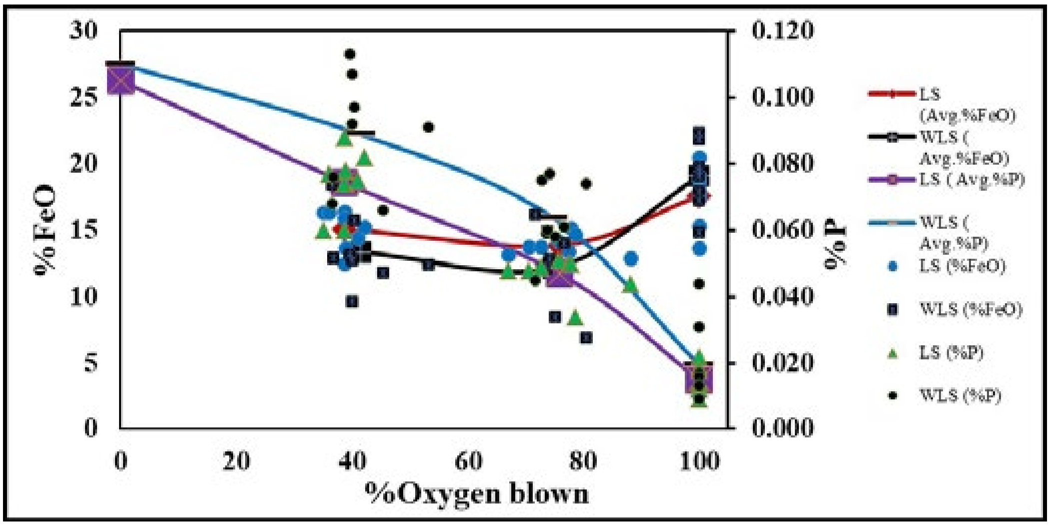

Fig.3 - Variation of wt. %FeO and wt.%P as blowing proceeds with and without ladle slag addition. (LS-with ladle slag addition, WLS-without ladle slag addition).

End of blow period

Last stage or end of blow period is characterised by weak decarburization reaction as carbon is depleting towards the end of blow. Majority of oxygen is utilized generating FeO, temperature starts to increase with decrease in slag viscosity of slag. Lime dissolution approaches towards completion and favourable conditions for dephosphorization are maintained. The comparison of slag formers addition on the basis of process parameters with and without ladle slag addition is presented in Table 4. It is observed that lime consumption was reduced by 1 tonne with addition of 2 tonnes of ladle slag is not affecting the steel refining. Slag basicity which is the direct measure of lime available in slag and it is higher with ladle slag addition. The slag basicity was continuously increasing from 2.8-3.1-3.3 for all three stages of blow with ladle slag addition while without its addition it was 1.8-2.7-3.2 in spite of higher lime addition as shown in Table 4. Figure 3 suggests that FeO level is increased from 12% to 19% and 14% to 17.5% for both with and without ladle slag addition for the 1st and last stage of blow while some reduction was seen in FeO level particularly in middle stage of blow for both. FeO level with ladle slag addition was higher for first two stages of blow but lower in the last stage of blow. This can be explained as iron ore addition was lower by approximately 800 kg with ladle slag addition as the cooling efficiency of ladle slag is almost 0.4 times of the iron ore and the iron ore addition was mainly done in the peak decarburization period. Hence, low iron ore addition during middle stage of blow resulted in low FeO level in the last stage of blow with ladle slag addition as shown in Table 5. The ladle slag addition effect is also visible in the opening temperature of steel bath. Hot metal temperature difference between normal heats and with ladle slag addition was 34°C and it was higher for normal heats and almost same difference of 30°C was observed end of blow stage. Input and output temperature difference was same for both trial conditions with reduction of 800 kg of iron ore. Average turndown phosphorus with ladle slag addition trials was 0.015% while it was 0.020% for normal heats. Dephosphorization efficiency was slightly better with ladle slag addition that is 85% while it was 82% for normal heats with reduction in lime and iron ore consumption by 1 tonne and 800 kg respectively. Dephosphorization efficiency is not compromised even by maintaining low FeO level in the turndown steel. As, high FeO in slag reduces viscosity [37] and may reacts with MgO present in the refractory and erosion occurs. Thus by maintaining low FeO level in the slag with ladle slag addition at the end of blow does not have any adverse effect on refractory erosion. Moreover, low FeO level in the last stage of blow will help in improving iron yield by approximately 200 kg compared

Tab.4 -Comparison of slag formers addition on the basis of process parameters: with and without ladle slag addition.

Parameters	Unit	Normal heats*	Heats with Ladle slag addition	Difference
Hot Metal	T	136	136	±0
Scrap	T	12	12	±0
C in HM	wt.%	4.2	4.3	±0.1
Si in HM	wt.%	0.60	0.60	±0.0
P in HM	wt.%	0.105	0.111	±0.006
HM Temperature	K	1650	1616	±34
Lime actual	Kg	8415	7416	-999
Dolomite	Kg	2623	2623	0
Iron Ore	Kg	3373	2541	-832
Ladle Slag	Kg	0	2000	2000
Tapping temperature	K	1976	1946	-30
Oxygen Slag Weight	Nm^3 T	7438 13.1	7457 14.3	19 1.2

Tab.5 - Comparison of important parameters for dephosphorization in steel during refining: with and without ladle slag addition.

	Normal Heats*			Heats with Ladle slag addition		
Parameters	2500-3500 Nm^3(B1)	4500-5800 Nm^3 (B2)	7000-7500 Nm^3 (EOB)	2500-3500 Nm^3 (B1)	4500-5800 Nm^3 (B2)	7000-7500 Nm^3 (EOB)
%FeO in Slag	13.3	12.1	19.0	15.1	13.8	17.5
Basicity	1.8	2.7	3.2	2.8	3.1	3.3
%P in steel	0.089	0.064	0.02	0.074	0.047	0.015
Temperature (K)	1793	1927	1976	1696	1868	1946
% Dephosphorization	19.8	42.3	82.0	26.9	53.6	85.2
L_P	9.8	21.2	96.8	14.3	34.1	113.2
Phosphate capacity	18.1	17.1	17.3	19.6	18.0	17.7

*Normal Heats: Heats without ladle slag addition, B1-1st stage of blow, B2-2nd stage of blow, EOB-End of blow

Slag analysis and weight at the end of blow stage

The slag former additions are mainly governed by hot metal, scrap weight and silicon content. Comparison of slag weight with and without ladle slag addition is presented in Figure 4. It may be observed that average slag weight is 1.2 tonnes higher with ladle slag addition compared to without its addition. Since, ladle slag is treated as slag formers, the total addition of slag formers increases, which ultimately increases the slag weight. Furthermore, the slag weight calculation is performed as a function of the hot metal silicon content. On average, the total amount of slag former additions is increased by 1001 (2000-999) kg when ladle slag is added considering the reduction in lime addition.

The two linear regressions in Figure 4 can be represented by the following equations;

With ladle slag (LS)

$$M_{SL} = 11.06x+7.87 \quad (5)$$

Without ladle slag

$$M_{SL} = 11.26x+6.99 \quad (6)$$

Figure 5 shows the average slag composition of heats with and without ladle slag additions. Minor differences in Al_2O_3 and FeO contents was observed with and without ladle slag heats however in other components the differences are negligible. Amount of alumina in BOF slag is an important parameter for consideration while using ladle slag as it contains high alumina (8-18%). It is mentioned in the literature [27] that high alumina content of the BOF slag hinders the dephosphorization reaction by stabilizing calcium-aluminium-ferrite and reduces the amount of C_2S and also the phosphorus content in C_2S. It was also reported that alumina content in BOF slag should be less than 4% in order to minimize its effect on dephosphorization efficiency.

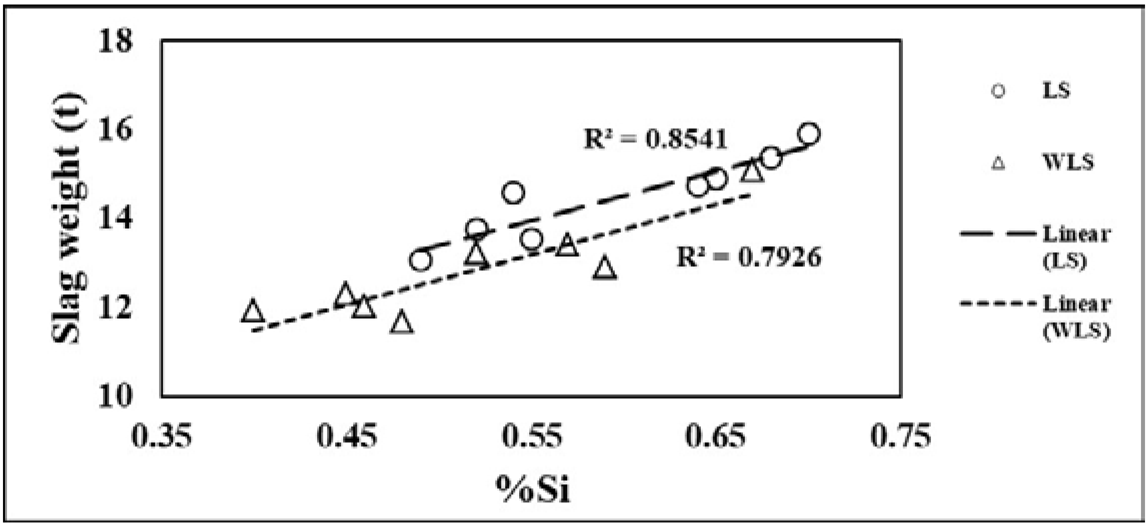

Fig.4 - Comparison of slag weight with and without ladle slag addition.

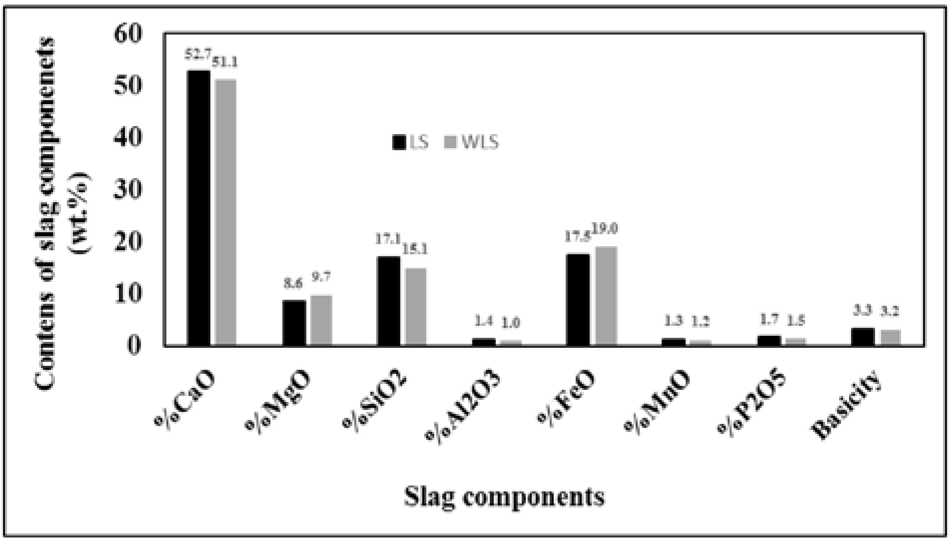

Fig.5 - Average slag composition of heats with and without ladle slag additions.

High alumina content particularly in the 1st stage of blow with ladle slag addition heats was observed in the present study. Figure 6 shows the variation of alumina in slag for all three stages of blow with and without ladle slag addition. Alumina content in the slag was 1.3-1.3-1.4% and 1.0-1.1-1.0% with and without ladle slag addition for all three stages of blow. Maximum alumina was found to be 2% in one heat with ladle slag addition while its average value was less than 1.5% in all stages of blow.

Phosphorus partition ratio and phosphate capacity of BOF slag

Phosphorus refining is not only dependent on the FeO content and basicity of slag but it is also strongly depending on the tapping temperature as shown in Figure 7. It can be seen that the phosphorus partition ratio is decreased with an increased tapping temperature. Moreover, noticeable difference in the phosphorus partition ratio is seen between normal and with ladle slag heats. Average partition ratio with ladle slag addition was 14-34-113 for all three stages of blow while it was 10-21-97 for normal heats. Higher partition ratio resulted in lower turn down phosphorus with ladle slag addition heats compared to normal heats. Turn down phosphorus with respect to tapping temperature is plotted in Figure 8 and it shows that content of turn down P in steel increases with increasing temperature. Average phosphorus for normal heats was 0.02% while it is 0.015% with ladle slag trial heats. This may be due to the favourable conditions required for dephosphorisation is achieved by ladle slag addition such as high basicity, low opening temperature and optimum FeO level.

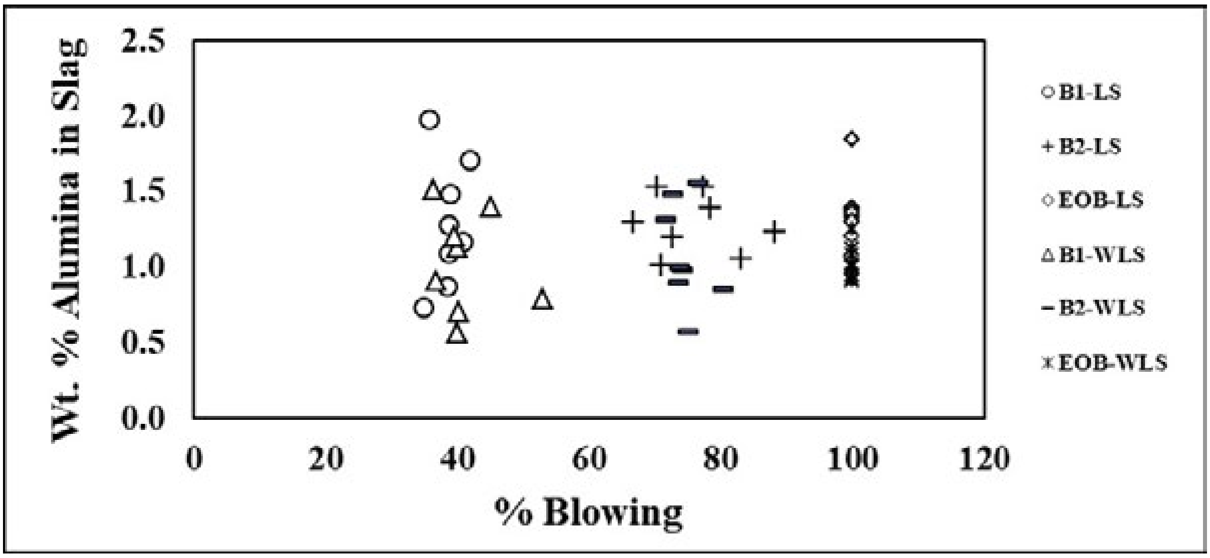

Fig.6 - Variation of alumina content with and without ladle slag addition in BOF: with and without ladle slag addition.

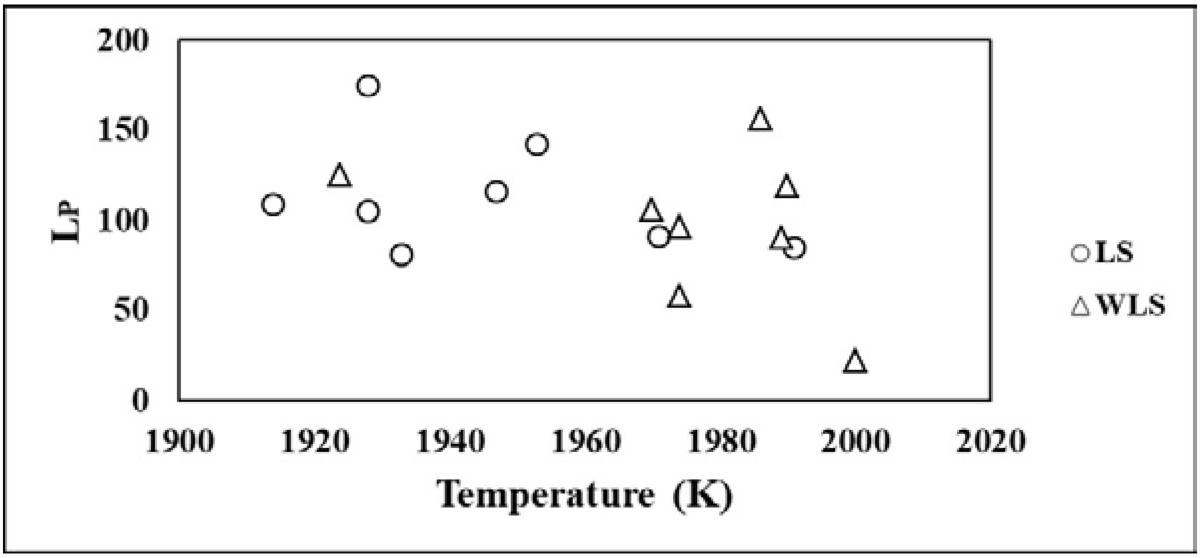

Fig.7 -Variation of L_P as a function of opening temperature in BOF: with and without ladle slag addition.

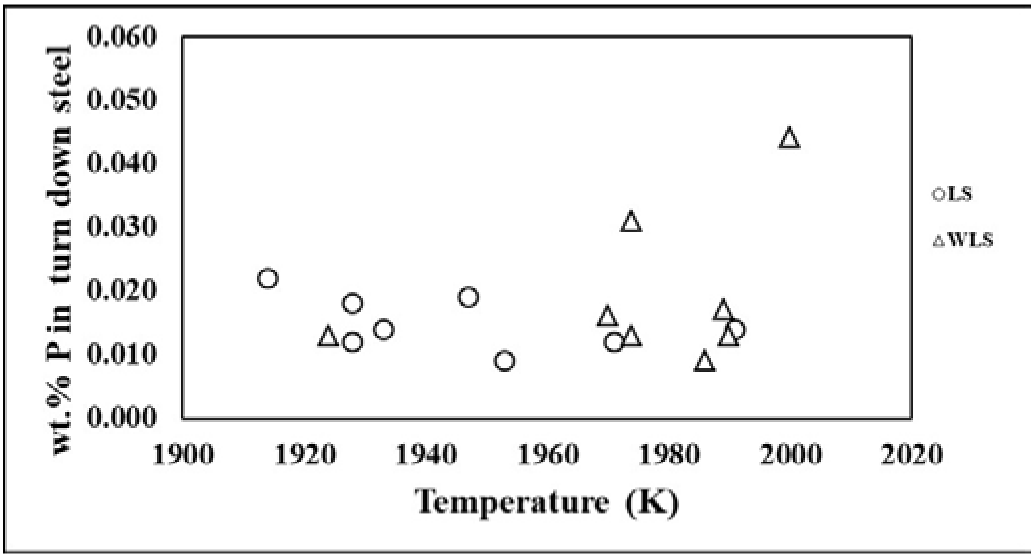

Fig.8 - Turn down phosphorus content in steel as a function of temperature in BOF: with and without ladle slag addition.

Phosphorus partition ratio is also dependent on the MgO content of slag. Chen et al. [38] and Basu et al. [39] conducted trials in industrial converter and found that the sudden decrease in L_P with increasing MgO is attributed to the significantly decreasing the activity coefficient of FeO and increasing the activity coefficient of P_2O_5. Phosphorus partition ratio is also plotted with respect %MgO in slag as shown in Figure 9. It is following the same trend as LP decreases with increase in MgO content of slag. It was observed that MgO level in all stages of slag contains less wt.% MgO with ladle slag addition compared to normal heats. This may be due to dilution effect as slag weight is more for heats with ladle slag addition.
Phosphate capacity of slag was calculated for all three phases of blowing and is plotted against the temperature as shown in Figure 10. From the results, it was observed that it decreases with an increase in temperature. The findings are consistent with the reported results [40-42].

This is due to the stability of ($\%PO_4^{3-}$) ion in the slag. Average phosphate capacity of BOF slag with ladle slag addition was slightly better than that of normal heats and it was presented in Table 5.

Blow condition

In some heats, soft blow was observed particularly near about 3000-4000 Nm^3 of oxygen. This may be due to low melting point of ladle slag which dissolves fast and form high slag volume. This soft blowing tendency was corrected by modifying the lance profile. The comparison of lance profile is presented in Table 6. Changing initial blowing height from 2.8 m to 2.4 m helped in controlling the slag volume and the soft blowing tendency was controlled.

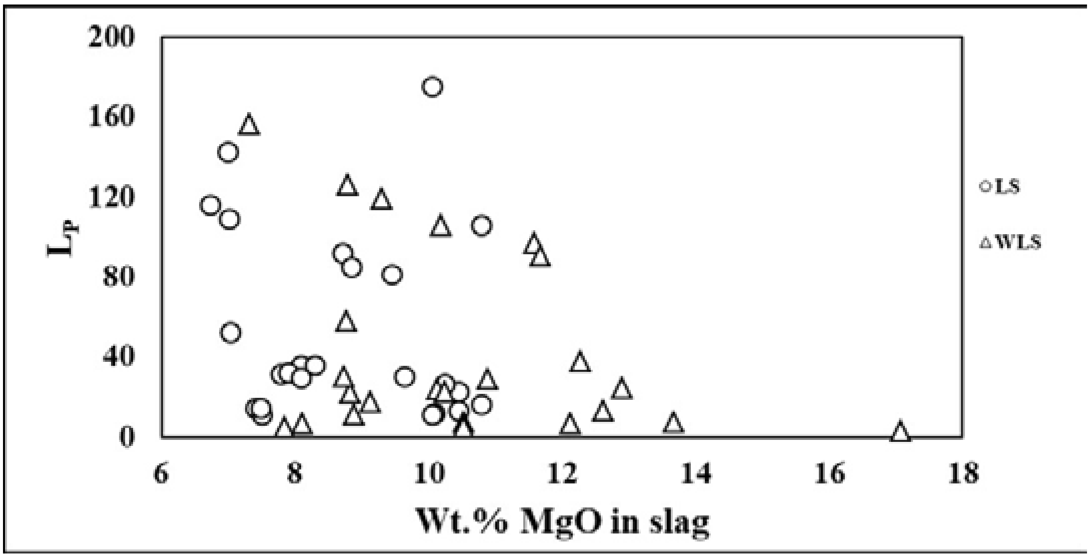

Fig.9 - Variation of L_P as a function of wt. %MgO in BOF slag: with and without ladle slag addition.

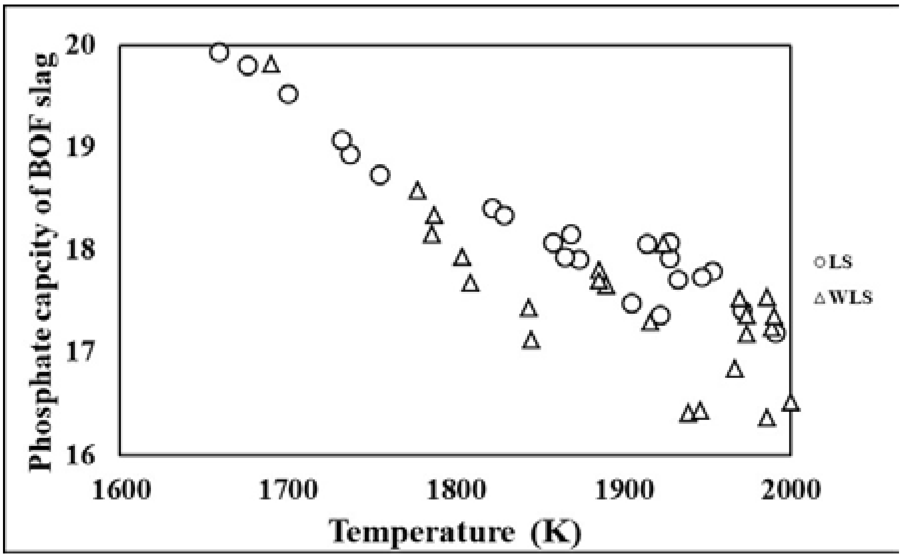

Fig.10 -Variation of phosphate capacity of BOF slag as a function of temperature-with and without ladle slag addition.

It was also observed that ladle slag addition is a function of Si content of the hot metal. Hence, ladle slag addition is encouraged to more than 2 tonnes (2.5 tonnes), when silicon content of hot metal was less than 0.4%. Because at such low Si level, slag formation is difficult and slag volume required for refining is inadequate. Ladle slag addition may solve this problem. In similar way, ladle slag addition should be reduced be restricted to below 2 tonnes when Si level is more than 0.8% while for Si level in between 0.41-0.80% Si which is also the case of this present study, 2 tonnes of ladle slag was added. The ladle slag addition chart as a function of ladle slag is presented in Table 7.

Tab.6 - Blowing lance profile:

Existing lance profile		**Modified lance profile**	
Lance Height (m)	Oxygen blow range (Nm^3)	Lance Height (m)	Oxygen blow range (Nm^3)
2.8	1-1600	2.4	1-2000
2.6	1601-2800	2.2	2001-5000
2.4	2801-3600	2.0	5001-6500
2.2	3600-4100	1.8	6501-blow end
2.4	4101-4800		
2.0	4801-6500		
1.8	6501-blow end		

Tab.7 - Ladle slag addition chart as a function of silicon content of hot metal.

S No.	Wt.% Si in hot metal	Amount of ladle slag to be added per heat (kg)	Lime saving per heat (kg)	Remarks
1.	0.35-0.50	2500	1200-1300	Lime saving is 50-60% of the ladle slag addition
2.	0.51-0.80	2000	1000-1100	
3.	0.81-1.00	1500	700-800	

CONCLUSIONS

The objective of this study was to investigate the effect of recycled ladle slag in BOF on various parameters such as partial replacement of lime with ladle slag, slag formation particularly in early stage of blow, steel quality (dephosphorization efficiency), vessel lining erosion and ease of blowing operation. The results are summarized below.

1. Melting point of ladle slag was measured with the help of Ash Fusion equipment. It was found that melting range of ladle slag is varying from 1653-1693 K. Hence, average melting point taken in this study was 1673 K.
2. In the present study, it was observed that for every 2 tonnes of ladle slag addition, lime consumption is reduced by 1 tonne per heat. Hence, specific lime consumption is reduced by 7.5 kg per tonne of crude steel.
3. Ladle slag addition helped in early slag formation. This is established with the help of intermediate steel and slag samples. Average slag basicity with ladle slag addition in 1st stage of blowing i.e., B1 was found to be 2.8 as compared to 1.8 without its addition. The slag basicity is increased in spite of low lime addition with ladle slag addition.
4. Dephosphorization efficiency of heats with ladle slag addition was slightly better than without its addition. This is further confirmed with the partition ratio and phosphate capacity of BOF slag; both showed improved results with ladle slag addition.
5. Cooling effect of ladle slag is estimated with the help of thermodynamics and it is compared with iron ore addition. It was estimated that cooling efficiency of ladle slag is 0.42 times of iron ore. Hence for every 2 tonnes of ladle slag addition, iron ore consumption is reduced by 800 kg per heat (6 kg per tonne of crude steel).
6. High cooling effect of ladle slag resulted in reduction

of iron ore requirement during blowing in order to get optimum opening temperature. This results in low FeO generation in the blow end period and helped in improving the iron yield by approximately 200 kg per heat. However, low FeO generation has no adverse effect on dephosphorisation efficiency as well as on refractory erosion with ladle slag addition.

7. It was observed that slag weight is slightly increased with ladle slag addition by 1 tonne per heat. The same has been observed in the previous studies of several authors.

8. In some heats, soft blow was observed; this is due to early slag formation with ladle slag addition (low melting temperature). The same has been addressed by modifying the lance profile.

9. Ladle slag addition chart as a function of hot metal silicon level was also presented in this study.

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ASSOCIAZIONE ITALIANA DI METALLURGIA

ASSOFOND
ASSOCIAZIONE ITALIANA FONDERIE

CORSO

PRIMA EDIZIONE

Fonderia per non fonditori

30 GIUGNO 1-7-8-12-13-14 LUGLIO 2022

Il settore della fonderia italiana è caratterizzato dalla presenza di oltre 1000 imprese, ripartite per specializzazione di produzione (176 fonderie di metalli ferrosi e 843 fonderie di metalli non ferrosi) e si posiziona al 12° posto del ranking mondiale con una produzione di 1,6 milioni di tonnellate di getti di cui circa 900.000 tonnellate ferrosi e circa 660.000 tonnellate non ferrosi. Grazie alle notevoli capacità di innovazione, sviluppate in questi anni dalle Imprese del Settore, la produzione di semilavorati e/o prodotti finiti per la gran parte dei Settori industriali, la tecnica di fonderia rappresenta oggi una tecnologia insostituibile per soddisfare le esigenze delle industrie Committenti.

La possibilità di utilizzare una vasta gamma di leghe ferrose e non ferrose, con caratteristiche chimico fisiche e tecnologiche tali da consentire la piena libertà progettuale nella realizzazione dei getti, in ogni forma e dimensione, pongono la tecnologia della fusione tra le soluzioni costruttive più convenienti per realizzare pezzi da pochi grammi ad oltre 100 tonnellate di peso unitario, con caratteristiche meccaniche e tecnologiche ai più elevati standard dei materiali da costruzione.

Mediante il processo attuato nella fonderia è possibile realizzare una serie di prodotti finiti (getti), con caratteristiche fisiche, metallurgiche e dimensionali ben definite, colando direttamente il metallo allo stato liquido in una opportuna forma che riproduce, in negativo, la geometria esterna del pezzo da ottenere, lasciandovelo poi solidificare e raffreddare. In questo contesto, allo scopo di fare conoscere la tecnologia di fonderia, le caratteristiche dei materiali formati e colati, i vantaggi ed i limiti legati alla tecnica di produzione dei pezzi realizzati per formatura e colata e al loro più razionale impiego nelle varie applicazioni, l'Associazione Italiana di Metallurgia ed Assofond (Associazione Italiana Fonderie) sono lieti di organizzare un corso di base rivolto a tutte quelle persone che quotidianamente sono coinvolte nell'acquisto, nella progettazione, collaudo e nell'utilizzo di particolari realizzati per formatura e colata di leghe Ferrose e non Ferrose, così da offrire l'opportunità di approfondire ai "non addetti ai lavori" le proprie conoscenze sul settore e su ciò che la tecnica di fonderia è in grado di offrire, allo scopo di favorire i rapporti tra fonderia e potenziali Committenti/utilizzatori di getti, nell'interesse reciproco e consentire nel contempo un'azione formativa nel settore alle nuove leve operative.

Il Corso è dedicato alla conoscenza delle principali famiglie di leghe e alle loro proprietà, ai criteri di selezione e di progettazione in funzione degli impieghi, affrontando gli aspetti che riguardano la metallurgia, le caratteristiche chimiche, fisiche e meccaniche, i trattamenti termici, la resistenza alla corrosione, la solidificazione, le tecnologie di produzione, i controlli, i difetti, la saldatura, l'impatto ambientale dei processi produttivi, il mercato italiano e mondiale. Il Corso si articolerà in sette giornate, per un totale di 28 ore. Alla fine di ogni giornata i docenti saranno a disposizione per approfondire i temi trattati.

Coordinamento

Prof. Giovanni Maria Caironi

30 giugno 1-7-8-12-13-14 luglio 2022

totale ore: 28

Da remoto:
Modalità sincrona
Diretta live su piattaforma Zoom

Modalità asincrona
Registrazioni su canale Youtube

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Fair Remote Training
organizzato dal Centro di Studio AIM/Assofond per la **Fonderia**

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