World Academics Journal of Engineering Sciences
Vol.9, Issue.1, pp.07-17, March (2022)

Research Paper

E-ISSN: 2348-635X

Comparative Study between Pure Calcium Cored Wire and Conventional Cored Wire (CaSi, CaFe) Addition for Secondary Refining of Steel

Kumar Abhishek[1*], Rajib Khanda[2], Dipankar Biswas[3], Kiran Kumar Keshari [4], K Rama Krishna[5]

[2,3,4]IISCO Steel Plant, SAIL, Burnpur, West Bengal, India
[1]RDCIS, SAIL, Burnpur, West Bengal, India
[4]RDCIS, SAIL, Ranchi, Jharkhand, India

[*]*Corresponding Author: kumarabhisheknit1@gmaill.com*

Available online at: www.isroset.org

Received: 28/Jan/2022, Accepted: 10/Mar/2022, Online: 31/Mar/2022

***Abstract*—**With over five years of experience of using conventional cored wire (CaSi/CaFe), the steel melting shop under consideration felt the need for switching over to an alternate option in view of the problems, like low yield, high wire consumption, frequent wire breakage during wire feeding and SEN clogging, faced with conventional wire. For this, and to keep up with the changing trend in steel plants worldwide in secondary refining technology, the shop turned to the use of pure Ca cored wire for better results. For exploring the benefits of this type of wire under the shop's operating conditions, plant trials were conducted with pure Ca cored wire from three different suppliers on supply and application basis.
From this exercise, it was found that pure Ca cored wire fared better than conventional wire on all fronts. Substantial difference was found in yield and wire consumption of the two types of wire. Wire consumption decreased by more than half and yield improved almost four times. These results were substantiated by data and plots in the study. Secondary refining time reduced but was not appreciable. Other noticeable benefits included no wire breakage during wire feeding, no clogging during casting and higher shelf life of the wire apart from consistency in result. The trials proved pure Ca cored wire to be a promising substitute for conventional wire. Therefore, the plant is looking forward to establish its usage at its steel melting shop. The aim of this paper is to present a succinct description of the details of the trials.

***Keywords*—** conventional wire, pure Ca wire, Ca cored wire, CaSi, CaFe, recovery

1.0 INTRODUCTION

In the process of molten steel refining, calcium silicon cored wire is commonly applied in aluminium-killed (Alk) steels at the end of refining treatment for sulphide shape modification and inclusion flotation mainly alumina (Al_2O_3) in the form of calcium aluminates. The core of calcium silicon wire is filled with powdered calcium silicide (CaSi) (minimum 30 % Ca and around 60 % Si) and the exterior is wrapped with steel sheet. However, this type of wire has some associated disadvantages, like uneven powder distribution, wastage of Ca by oxidation during transportation and storage resulting in low Ca yield, Si pick up in low Si steel grades, frequent wire breakage, to mention a few.

The type of CaSi wire used at this steel melting shop (SMS) has a diameter of 13 mm and linear weight 230 gm/m. More than five years of experience of using CaSi/CaFe wire led the shop to the following conclusions:
Heats of a wide range of steel grades are made at SMS. The product mix includes semi killed and killed steel grades. While for most of the grades, CaSi wire is suitable; for grades like EWNR and CAQ, CaFe wire is the preferred material owing to the low Si demand in these grades in the final product. As a result, the shop had to switch between CaSi and CaFe wires frequently as per the production plan. This was an impediment of logistics nature in smooth production.

Another problem posed by CaSi/CaFe wire was poor recovery of Ca. This necessitated the operators to add CaSi/CaFe to the tune of 1000 m in Al-killed grades to achieve the desired level of Ca in the bath. Due to this, both material consumption and ladle furnace (LF) treatment time increased. This also adversely affected the techno-economics of the process.

Inconsistency in recovery values was another problem associated with conventional wires and made it very difficult for the shop to achieve the desired Ca value in one injection. As a result, stopper erosion, clogging tendency during casting, all were observed for the same injection parameters in the same grade with conventional wires.
In order to take care of all such problems, various cored wire manufacturers have come up with a new type of cored

wire i.e. solid pure Ca cored wire (henceforth, will be referred to as pure Ca wire in the report). This type of wire is a high performance cored wire filled with high purity Ca additive in solid wire for treatment of steel. It reduces cost by bringing down addition rates & ensures consistent recovery. Longer shelf life, uniform Ca distribution, high recovery rate, reduced nozzle clogging, less wire breakage and improved steel cleanliness are some of the benefits due to which this type of wire is gaining ground across different steel plants worldwide.

To tap the benefits of pure Ca addition, SMS decided to go for trials of pure Ca wire via two modes: firstly, trials of 10 tons of pure Ca wire supplied by Supplier#1 and secondly, trials to be taken under total calcium management (TCM) (Supplier#2 for 70,000 tons of steel and Supplier#3 for 30,000 tons of steel). In view of this, the present paper aims at assessing the techno-economic implications of adding pure Ca wire compared to that of CaSi/CaFe wire under the shop's operating conditions.

2.0 EXPERIMENTAL / WORK DONE

The steel plant has 2x150 ton LFs, which receive heats from 3x150 ton basic oxygen furnaces (BOF), process them, and cater to 2x6 strand billet casters and a 1x4 strand bloom-cum-beam blank caster. Around 45 heats are treated every day in the LFs of the steel melting shop.

During the trials, the heat making process at SMS started from hot metal de-sulphurisation station (HMDS). All special steel grades were necessarily subject to de-sulphurisation to make them conducive for Ca treatment along with other advantages. This was followed by the charging of the heats in the converters for primary refining. After primary refining, the heats were tapped in steel ladles and transferred to the LF station for secondary refining. Each of the LFs has a 1x2 strand PLC controlled wire feeder. Figure 1 is the schematic of wire feeding through a wire feeder. To conduct the trials, pure Ca wire was installed in one of the strands of the LF#1 wire feeder; the other strand had aluminium (Al) wire. The wire feeders of the LFs are designed to operate with 13 mm diameter wire. To make the feeders compatible with 9 mm wire, suitable arrangements were made to avoid wire slippage during operation.

During the trials at LF#1, the final treatment of secondary refining was performed with pure Ca wire injection through the wire feeder. The trials were conducted by varying the amount of material injected. Moreover, in almost all the trial heats, the injection rate was kept 125 m/min compared to 250-300 m/min in the case of conventional wire. Soft Argon purging of heats was performed for 5 minutes after Ca addition to ensure complete modifications of inclusions. Exposure of melt with atmosphere was avoided/minimized after Ca addition through controlled gas purging. Slag oxygen potential was controlled to avoid re-oxidation of Al by the slag.

Post secondary refining, the heats were sent to the casters. Collection of metal samples from liquid steel in tundishes is a regular practice in the shop. For Ca level readings post wire feeding, analyses of these metal samples have been considered in the study. For performance assessment, primarily Al-treated grades, like EWNR, SAE1006 (CAQ), SAE1008 (CAQ), SAE1010 Alk, SAE1018 Alk and Sail Tower Alk have been taken. To avoid the formation of CaS, care was taken not to add pure Ca in inadequately de-sulphurised heats, i.e., heats with more than 0.015% S.
Trial data was noted down on a regular basis to create an experimental database. The databases of base data and the experimental data formed the basis of data analysis for carrying out comparative study. For data analysis, the R software was used.

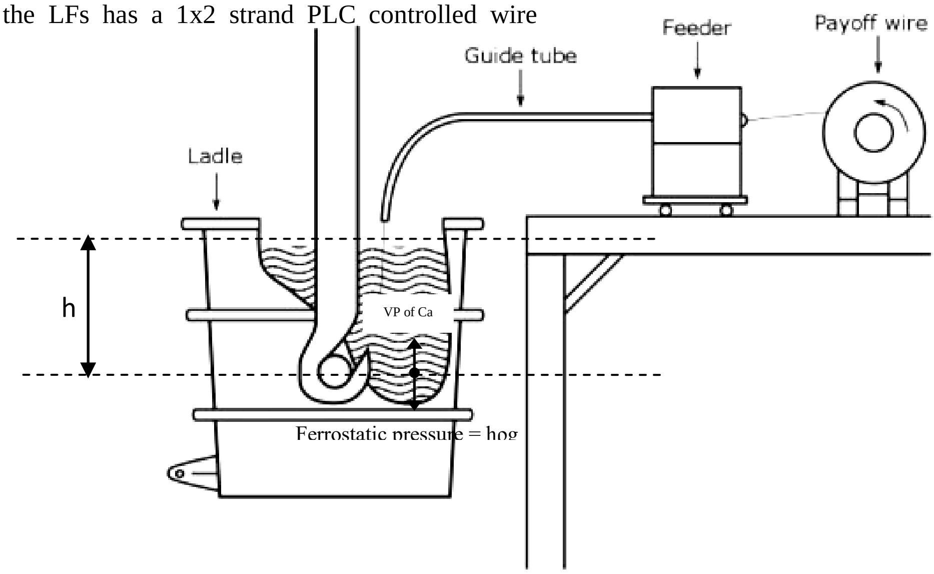

Fig. 1: Calcium wire feeding process

3.0 RESULTS AND DISCUSSION

3.1 Base study

The purpose of the base study was to comprehend the conditions under which the experiments were to be performed. The experimental conditions relevant to the present study primarily included the types of steel grades being made at the SMS and their heat making processes. The performance of Ca treatment differs from grade to grade depending upon the grade's chemistry, viz., Al level, oxidation potential, S level etc.

Like other ferroalloys, the recovery of pure Ca is also dependent on the oxidation potential of slag and liquid steel; the lesser the oxidation potential the more the recovery. Irrespective of the grade being made, the turndown dissolved oxygen ([O]) level at the SMS is usually in the range of 700-900 ppm. Post tapping, the grade specific de-oxidation pattern is followed, which the shop has developed over time. The shop makes both Al-treated semi-killed and killed steel grades due to its diversified product basket. Al-treated semi-killed grades include EWNR, SAE1006 (CAQ) and SAE1008 (CAQ), whereas Alk grades include SAE1010 Alk, SAE1018 Alk and Sail Tower Alk. The specification of the above grades and their LF out slag chemistries are given in Table 1.

Table 1(a): Chemistry of grades considered for performance evaluation

Grade	C%	Si%	S%	P%	Mn%	Al%
EWNR	0.10 max	0.03 max	0.025 max	0.025 max	0.38-0.62	0.012 max
SAE1006 (CAQ)	0.08 max	0.07 max	0.025 max	0.025 max	0.25-0.35	--
SAE1008 (CAQ)	0.10 max	0.1 max	0.030 max	0.030 max	0.30-0.50	--
SAE1010 Alk	0.08-0.13	--	0.030 max	0.030 max	0.30-0.50	0.020 min
SAE1018 Alk	0.15-0.20	--	0.030 max	0.030 max	0.60-0.90	0.020-0.055
Sail Tower Alk	0.15-0.22	0.15-0.30	0.045 max	0.045 max	1.15-1.60	0.020 min

Table 1(b): Chemistry of LF slag of grades in Table 1(a)

Grade	CaO%	SiO_2%	Al_2O_3%	MgO%	Fe_tO%	MnO%
EWNR	45-50	25-30	05-15	05-10	<3.0 (avg. 1.7)	<5.0 (avg. 2.5)
SAE1006 (CAQ)	45-50	25-30	05-15	05-10	<3.0 (avg. 1.0)	<5.0 (avg. 1.2)
SAE1008 (CAQ)	45-50	25-30	05-15	05-10	<3.0 (avg. 1.1)	<5.0 (avg. 1.4)
SAE1010 Alk	45-50	25-30	10-20	05-10	<1.0	<1.5
SAE1018 Alk	45-50	25-30	10-20	05-10	<1.0	<1.5
Sail Tower Alk	45-50	25-30	10-20	05-10	<1.0	<1.5

The target [O] level of semi-killed heats is ~30 ppm and that for killed heats is $\leq$ 5 ppm approx, which are achieved by different Al treatment (or deoxidation pattern).

For Al-treated semi-killed heats, 200-250 kg Al is added, in the form of 20 kg blocks, during tapping with nil Al addition at the LFs. Consequently, the [Al] level achieved in tundish analyses is around 15-20 ppm. For mitigating the affect of alumina formed in the process, CaSi is added for SAE1006 (CAQ) and SAE1008 (CAQ) and CaFe for EWNR.

For killed heats, Al addition during tapping is around 250 kg, in the form of 20 kg blocks, during tapping. At the LFs, Al wire is fed to build-up a minimum of 0.02 % dissolved Al in the bath. Consequently, the average [Al] level achieved in tundish analysis is 0.03 %. Again, for mitigating the affect of alumina formed in the process, CaSi wire is added. However, in this case, CaSi wire consumption is more due to more alumina generation.

At the SMS, desulphurisation of heats is done mandatorily for all the above grades as these grades fall under special quality steel grades. As a result, the LF station receives heats with S less than 0.010 %. This level is well below the critical S level for Ca treatment, i.e., 0.015 %, mentioned in literature[1].

Data of around 100 nos. of heats made with this practice were collected and collated to form a database of base data. Figure 2 shows the wire addition pattern for different steel grades as per the conventional practice. The distribution of Ca recovery values resulting from this practice is given in Fig. 3. From the base data, the average recovery value from conventional wire was calculated to be 4.36 % with a standard deviation (SD) of 3.02 % (Fig. 4).

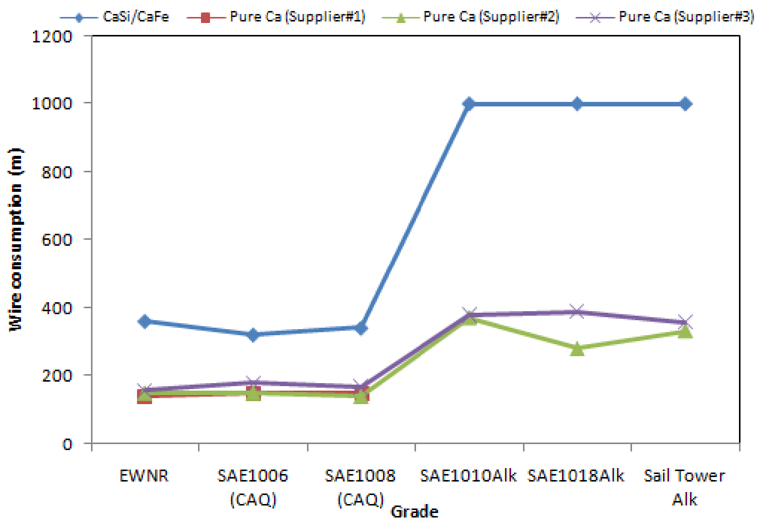

Fig. 2: Grade-wise comparison of wire consumption of conventional wire with pure Ca wire

3.2 TRIAL OUTCOMES

During the trials, the operational practices were the same as mentioned in the base study. From trial observation and data analysis, a marked difference was observed between the performance of pure Ca wire and conventional wire. An improvement in recovery, and decrement in wire consumption and LF treatment time were major technological outcomes of the trials. An injection rate of 125 m/min was found to be the best suited under prevailing conditions. Wire breakage and clogging incidences decreased sharply. Assuming that recovery is normally distributed, Fig. 4 summarizes the performance of conventional wire and pure Ca wire in terms of the average value and the spread (standard deviation) of recovery calculated from the base period data and the trial data. The middle points of both the curves represent the average recovery values, and the expanse of the curves represents the spread of the recovery values. The middle point of the pure Ca wire curve lies ahead of that of the conventional wire curve showing that the average recovery value of pure Ca wire is greater than that of conventional wire. Also, the pure Ca wire curve is more spread out compared to the conventional wire curve showing that the standard deviation of recovery of pure Ca wire is greater than that of conventional wire. From the trial data, the average recovery value obtained from using pure Ca wire was calculated to be 19.06 % with a standard deviation of 8 %.

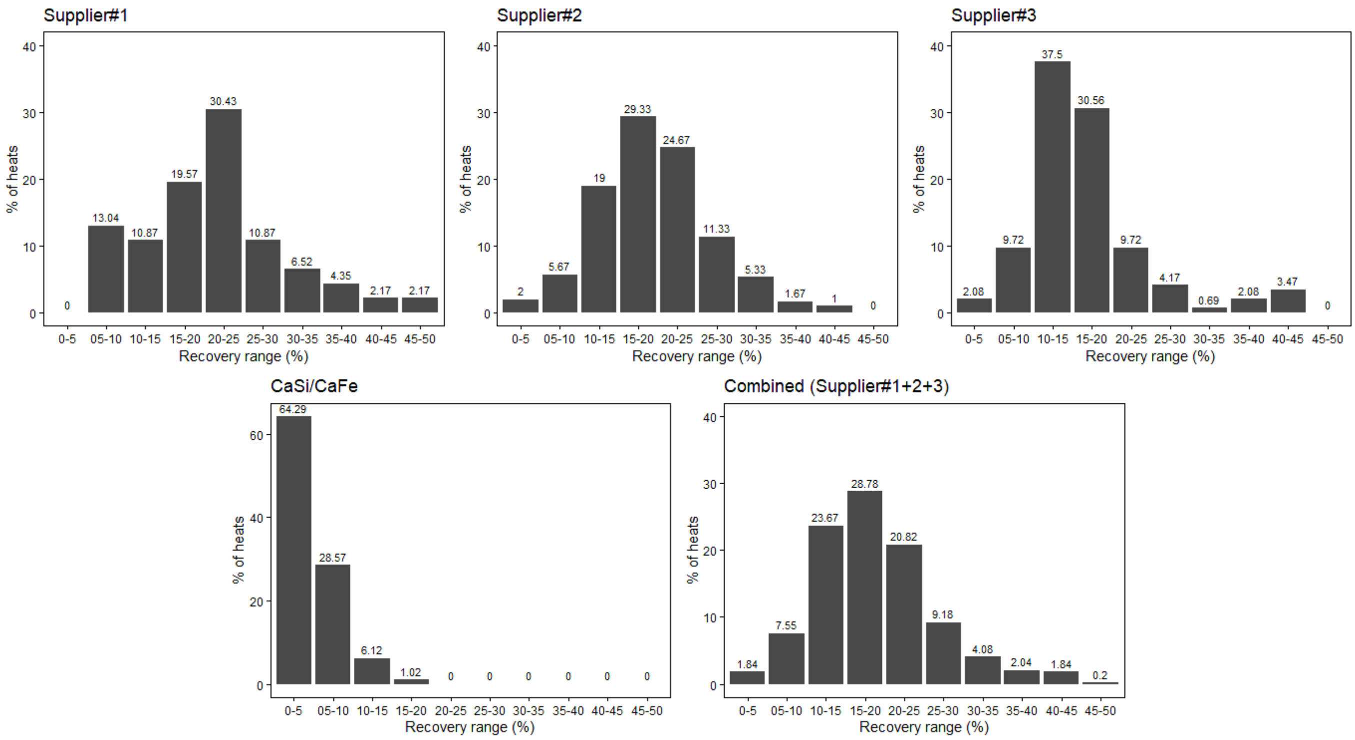

Fig. 3: Comparison of distribution of Ca recovery values for pure Ca wire and CaSi/CaFe wire

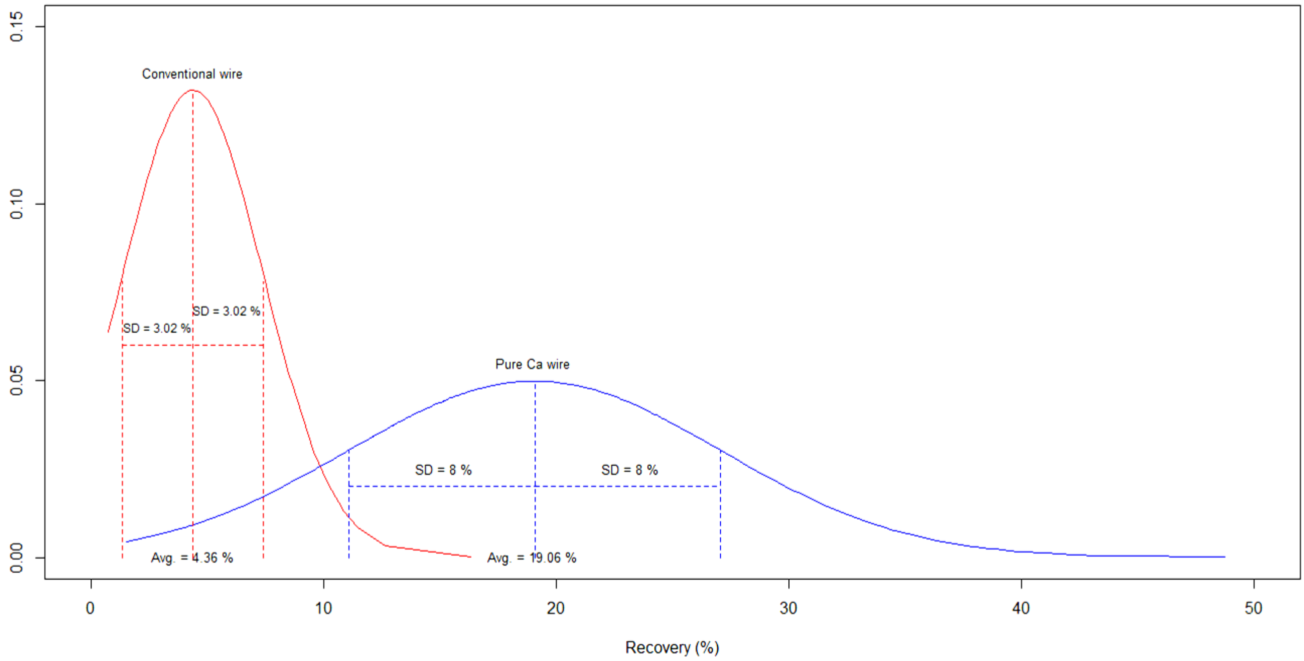

Fig. 4: Performance comparison between conventional wire and pure Ca wire by plotting normal distribution curves of recovery for both the cases

Talking about injection rate, 125 m/min was found suitable under prevailing conditions. However, it does not qualify as an advantage of pure Ca wire as this value is much less compared to 250-300 m/min of conventional wire. Notionally, high injection rate is desirable for deep penetration depth, hence high recovery. But, practically this does not happen. The variation of penetration depth and recovery with injection rate is shown in Fig. 5(a) and Fig. 5(b). This is due to the phenomenon that the thermal conductivity of filler material changes with injection rate. Therefore, when wire is injected in the bath, the penetration depth is decided by two effects, which counteract each other. Till a certain injection rate, the effect of increasing injection rate is more, which results into an increase in penetration depth. Beyond a certain value, the effect of high thermal conductivity (due to high injection rate) dominates, resulting into early melting of wire, hence low penetration depth. The value at which this change occurs is the best value of injection rate, and forms the basis of injection rate optimization. It may be noted that speed optimization is necessary for each cored wire type and is plant specific.

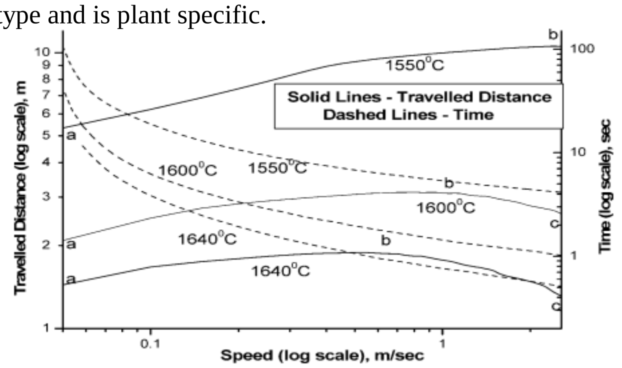

Fig. 5(a): Effect of injection rate (speed) on penetration depth (travelled distance)[2]

Figure 5(a) has been taken from a study conducted by R&D, Tata Steel[2]. The figure is the result of numerical simulation of cored wire injection taking into account different operating practices encountered in SMS. In the region of injection rate lower than the point ‘b’, the first factor dominates and thus, the distance travelled increases with the injection rate. After point ‘b’, the second factor becomes dominant and therefore as injection rate increases the distance travelled by the wire decreases in this region. The injection rate corresponding to the point ‘b’ is the best injection rate. Similarly, Fig. 5(b) has been taken from industrial trials conducted by MINEX Metallurgical Co Ltd[3]. In this figure, the behaviour of wire changes at an injection rate of 120 m/min. Hence, this rate is the best rate for the shop in which the trials were conducted.

In the case of the present trials, it was difficult to establish the aforementioned phenomenon as injection rate was not varied much. In more than 90 % of the trial heats, the injection rate was kept 125 m/min. This value gave good results.

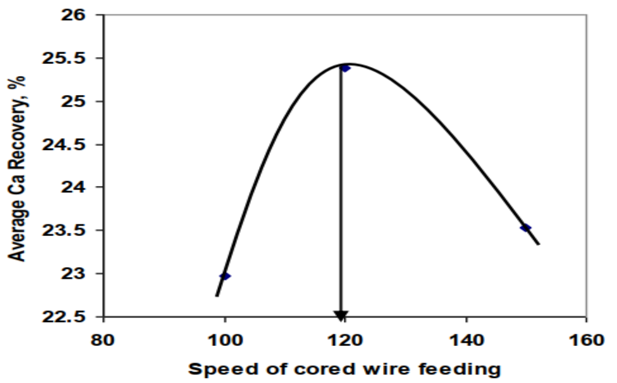

Fig. 5(b): Effect of injection rate (speed) on average calcium recovery[3]

Another important outcome of the trials was variation in pure Ca wire behaviour with respect to steel grades. The average value and standard deviation of recovery were calculated separately for semi-killed grades and killed grades. It was found that semi-killed grades exhibited higher average and standard deviation compared to killed grades, shown in Fig. 6. For better visualization of the spread of the recovery values for different steel grades, box plots were made as shown in Fig.7. The box plots give the five point summary (min., quartile 1, median, quartile 3, max) of the recovery values against each of the steel grades. Behavioural variation of pure Ca with respect to steel grades is shown in the figure. It shows that the recovery values are higher for semi-killed grades, with EWNR and SAE1006 (CAQ) showing excellent values, compared to killed grades. The observation holds true for all the three suppliers. Where most recovery values for EWNR and SAE1006 (CAQ) lies above 20 %, the same for killed grades are predominantly below 15 %. This also increases the standard deviation of recovery.

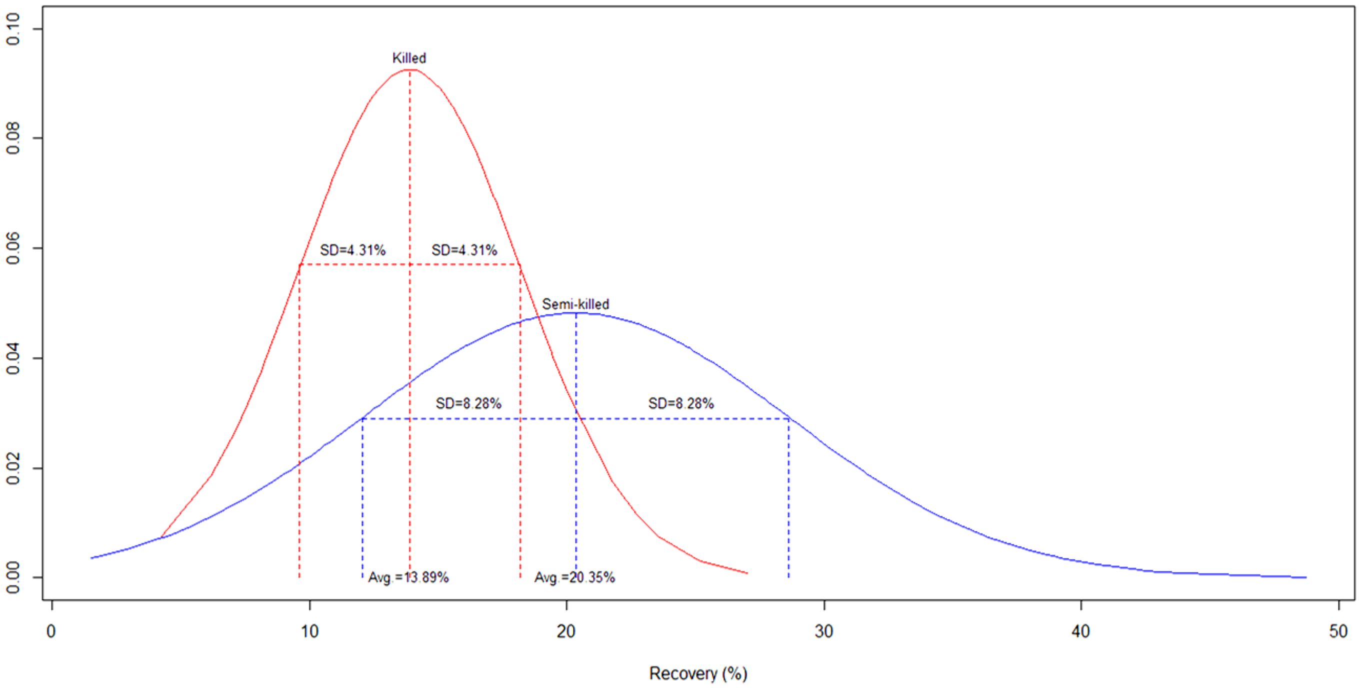

Fig. 6: Distribution of recovery for semi-killed grades and killed grades for pure Ca wire

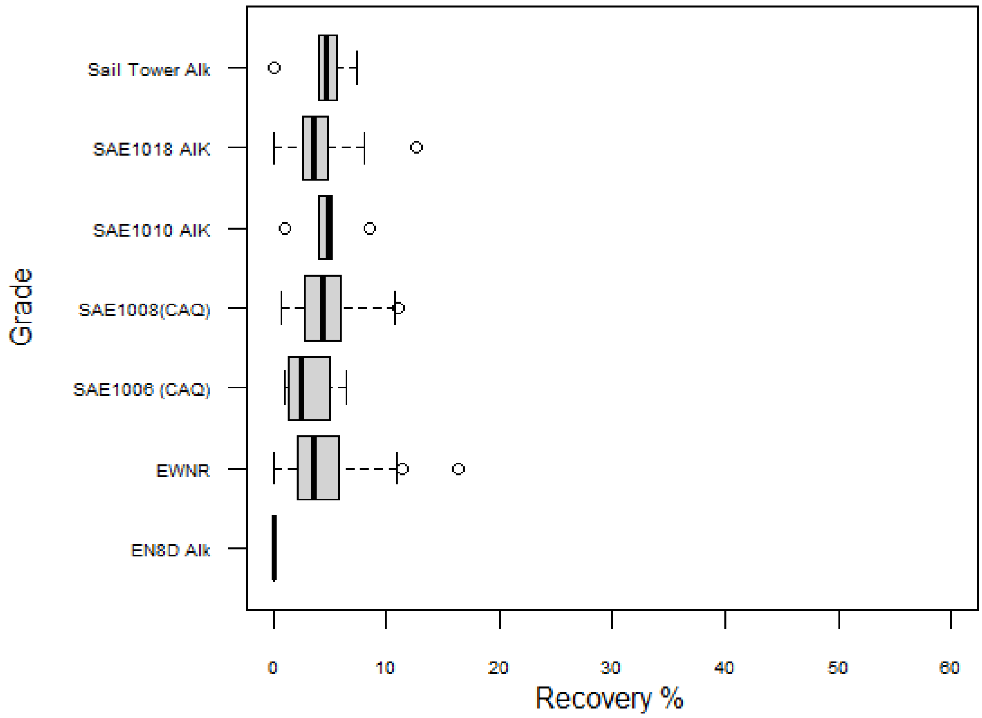

Fig. 7(a): Grade-wise spread of recovery values for conventional wire

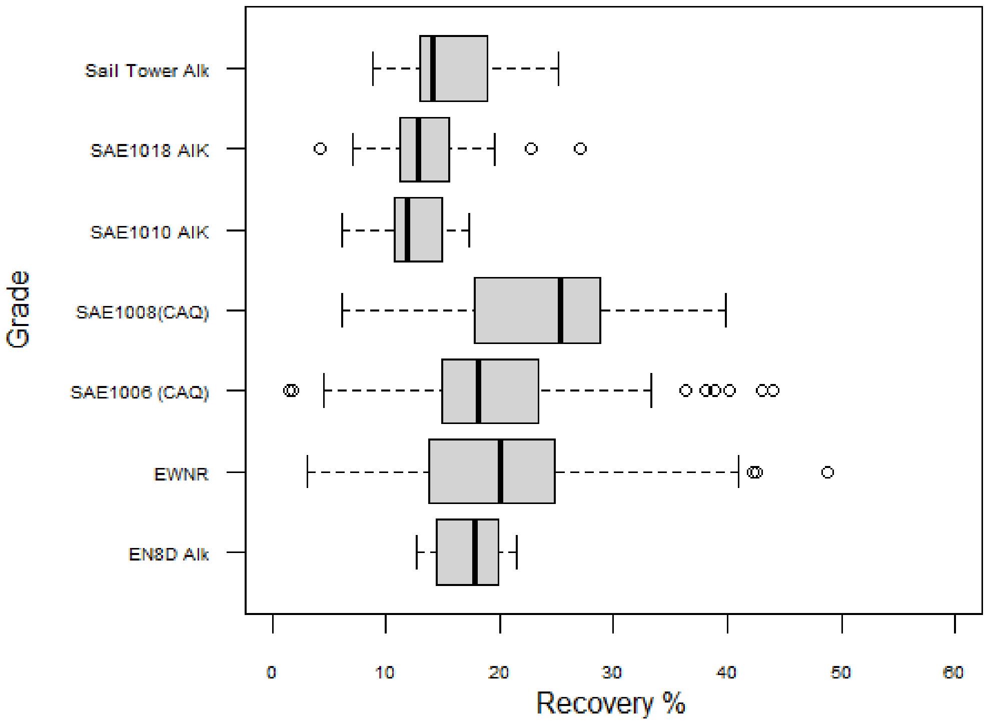

Fig. 7(b): Grade-wise spread of recovery values for pure Ca wire

The extent of fading of Ca after the ladles left the LF was also studied. The final chemistry of the bath is ascertained from the metal samples taken either from the LF after all additions or from the tundish. The practice varies from shop to shop. At the SMS where the trials were conducted, the practice of taking metal samples from the tundishes is followed in every heat. However, if time permits, LF final metal samples are also taken. During the movement of a ladle filled with liquid steel from the LF to the caster, chemical reactions continue due to dissolved oxygen in the bath. Consequently, slight variations are found between the analyses of LF samples and tundish samples. Variations predominantly occur in Si, Al and Ca[4]. In order to study this phenomenon under the shop's operating conditions with respect to Ca, in some heats both LF and tundish samples were taken to draw comparisons. The result is shown in Table 2. The table compares tundish Ca levels with LF out Ca levels, and recoveries calculated from tundish Ca readings with those calculated from LF out Ca readings. From the table, Ca fading is obvious and the extent of fading is substantial with an average fading % $((\Delta Ca_{LF\rightarrow Tundish}/Ca_{LF})*100)$ of -43.83 %. The average $recovery_{LF}$ is 36 % and the average $recovery_{Tundish}$ is 20 %.

Table 2: Ca fading from LF to tundish for pure Ca wire

Grade	**Amount (m)**	**LF Ca (ppm)**	**Tundish Ca (ppm)**	**$\Delta Ca_{LF\rightarrow Tundish}$ (ppm)**	**$\Delta Ca_{LF\rightarrow Tundish}$ (%)**	**$Recovery_{LF}$ (%)**	**$Recovery_{Tundish}$ (%)**
EWNR	200	0.0029	0.0021	-0.0008	-27.59	32.31	23.40
EWNR	156	0.0021	0.0013	-0.0008	-38.10	29.99	18.57
EWNR	147	0.0024	0.0014	-0.0010	-41.67	36.38	21.22
EWNR	147	0.0022	0.0016	-0.0006	-27.27	33.35	24.25
EWNR	147	0.0020	0.0017	-0.0003	-15.00	30.32	25.77
EWNR	147	0.0027	0.0018	-0.0009	-33.33	40.93	27.28
EWNR	147	0.0024	0.0012	-0.0012	-50.00	36.38	18.19
EWNR	190	0.0024	0.0017	-0.0007	-29.17	28.15	19.94
EWNR	147	0.0015	0.0010	-0.0005	-33.33	22.74	15.16
EWNR	200	0.0021	0.0013	-0.0008	-38.10	23.40	14.48
EWNR	147	0.0019	0.0015	-0.0004	-21.05	28.80	22.74
EWNR	147	0.0021	0.0010	-0.0011	-52.38	31.83	15.16

EWNR	162	0.0029	0.0019	-0.0010	-34.48	39.89	26.13
EWNR	206	0.0020	0.0015	-0.0005	-25.00	21.63	16.22
EWNR	177	0.0034	0.0017	-0.0017	-50.00	42.80	21.40
EWNR	177	0.0024	0.0013	-0.0011	-45.83	30.21	16.37
EWNR	156	0.0020	0.0009	-0.0011	-55.00	28.57	12.85
EWNR	177	0.0037	0.0015	-0.0022	-59.46	46.58	18.88
EWNR	125	0.0022	0.0007	-0.0015	-68.18	39.22	12.48
EWNR	147	0.0025	0.0002	-0.0023	-92.00	37.89	3.03
EWNR	120	0.0020	0.0007	-0.0013	-65.00	37.14	13.00
EWNR	147	0.0032	0.0013	-0.0019	-59.38	48.50	19.70
EWNR	147	0.0030	0.0016	-0.0014	-46.67	45.47	24.25
EWNR	147	0.0034	0.0017	-0.0017	-50.00	51.54	25.77
EWNR	155	0.0023	0.0015	-0.0008	-34.78	33.06	21.56
EWNR	155	0.0035	0.0018	-0.0017	-48.57	50.31	25.88
EWNR	150	0.0017	0.0012	-0.0005	-29.41	25.25	17.83
EWNR	140	0.0017	0.0005	-0.0012	-70.59	27.06	7.96
EWNR	147	0.0024	0.0017	-0.0007	-29.17	36.38	25.77
EWNR	147	0.0025	0.0016	-0.0009	-36.00	37.89	24.25
SAE1006 (CAQ)	147	0.0018	0.0008	-0.0010	-55.56	27.28	12.13
SAE1006 (CAQ)	147	0.0024	0.0014	-0.0010	-41.67	36.38	21.22
SAE1006 (CAQ)	145	0.0024	0.0010	-0.0014	-58.33	36.88	15.37
SAE1006 (CAQ)	150	0.0017	0.0012	-0.0005	-29.41	25.25	17.83
SAE1006 (CAQ)	100	0.0016	0.0006	-0.0010	-62.50	35.65	13.37
SAE1006 (CAQ)	162	0.0014	0.0008	-0.0006	-42.86	19.26	11.00
SAE1006 (CAQ)	162	0.0023	0.0020	-0.0003	-13.04	31.63	27.51
SAE1006 (CAQ)	162	0.0021	0.0010	-0.0011	-52.38	28.88	13.75
SAE1006 (CAQ)	100	0.0018	0.0012	-0.0006	-33.33	40.11	26.74
SAE1006 (CAQ)	147	0.0025	0.0011	-0.0014	-56.00	37.89	16.67
SAE1006 (CAQ)	122	0.0017	0.0008	-0.0009	-52.94	31.05	14.61
SAE1006 (CAQ)	147	0.0028	0.0016	-0.0012	-42.86	42.44	24.25
SAE1006 (CAQ)	147	0.0025	0.0011	-0.0014	-56.00	37.89	16.67
SAE1006 (CAQ)	147	0.0033	0.0013	-0.0020	-60.61	50.02	19.70
SAE1006 (CAQ)	147	0.0029	0.0015	-0.0014	-48.28	43.96	22.74
SAE1006 (CAQ)	147	0.0021	0.0010	-0.0011	-52.38	31.83	15.16
SAE1006 (CAQ)	147	0.0027	0.0020	-0.0007	-25.93	40.93	30.32
SAE1006 (CAQ)	147	0.0027	0.0022	-0.0005	-18.52	40.93	33.35
SAE1006 (CAQ)	147	0.0028	0.0012	-0.0016	-57.14	42.44	18.19
SAE1006 (CAQ)	147	0.0023	0.0015	-0.0008	-34.78	34.86	22.74
SAE1006 (CAQ)	88	0.0018	0.0008	-0.0010	-55.56	45.58	20.26
SAE1006 (CAQ)	103	0.0017	0.0011	-0.0006	-35.29	36.78	23.80
SAE1008 (CAQ)	120	0.0029	0.0012	-0.0017	-58.62	53.85	22.28
SAE1008 (CAQ)	153	0.0022	0.0011	-0.0011	-50.00	32.04	16.02
SAE1008 (CAQ)	147	0.0026	0.0014	-0.0012	-46.15	39.41	21.22
SAE1008 (CAQ)	147	0.0017	0.0004	-0.0013	-76.47	25.77	6.06

SAE1008 (CAQ)	147	0.0015	0.0011	-0.0004	-26.67	22.74	16.67
SAE1008 (CAQ)	88	0.0015	0.0012	-0.0003	-20.00	37.98	30.38
SAE1008 (CAQ)	88	0.0026	0.0011	-0.0015	-57.69	65.83	27.85
SAE1010-Alk	350	0.0031	0.0022	-0.0009	-29.03	19.74	14.01
SAE1010-Alk	350	0.0041	0.0019	-0.0022	-53.66	26.10	12.10
SAE1010-Alk	400	0.0056	0.0017	-0.0039	-69.64	31.19	9.47
SAE1010-Alk	403	0.0062	0.0031	-0.0031	-50.00	34.28	17.14
SAE1018-Alk	206	0.0034	0.0025	-0.0009	-26.47	36.78	27.04
SAE1018-Alk	206	0.0029	0.0021	-0.0008	-27.59	31.37	22.71
SAE1018-Alk	206	0.0028	0.0018	-0.0010	-35.71	30.29	19.47
SAE1018-Alk	294	0.0016	0.0010	-0.0006	-37.50	12.13	7.58
SAE1018-Alk	324	0.0033	0.0022	-0.0011	-33.33	22.69	15.13
SAE1018-Alk	324	0.0037	0.0012	-0.0025	-67.57	25.45	8.25
SAE1018-Alk	350	0.0041	0.002	-0.0021	-51.22	26.10	12.73
SAE1018-Alk	381	0.0063	0.0032	-0.0031	-49.21	36.84	18.71
SAE1018-Alk	410	0.0061	0.0028	-0.0033	-54.10	33.15	15.22
SAE1018-Alk	420	0.0042	0.0008	-0.0034	-80.95	22.28	4.24
SAE1018-Alk	434	0.005	0.0026	-0.0024	-48.00	25.67	13.35
SAE1018-Alk	441	0.0045	0.0034	-0.0011	-24.44	22.74	17.18

3.3 WHY PURE CA CORED WIRE IS BETTER THAN CONVENTIONAL CORED WIRE

Recovery

The main parameter chosen for performance evaluation was Ca recovery %, whose formula is as follows:

$$Ca\ recovery = \frac{change\ in\ Ca\%\ due\ to\ wire\ addition\ X\ heat\ size}{length\ of\ wire\ X\ wire\ density\ X\ purity\ of\ wire}\ X\ 100 \qquad Eq.1$$

It is very obvious from Fig. 3 and Table 3 that the recovery values of pure Ca wire are much better than those of conventional wire.

Table 3: Grade-wise comparison of recovery values of conventional wire with pure Ca wire

Grade	CaSi/CaFe	Pure Ca
EWNR	4.50	20.44
SAE1006 (CAQ)	3.00	19.35
SAE1008 (CAQ)	4.50	24.15
SAE1010 Alk	4.78	12.44
SAE1018 Alk	3.50	13.50
Sail Tower Alk	5.30	15.58

This can be attributed to the high vulnerability of Ca to oxidation in conventional wire. In conventional wire, the compactness of the wire core powder is less. Therefore, during transportation and storage, air makes its way into the gaps of the wire core and oxidises Ca. Net Ca availability per unit length of wire decreases. When wire in this condition is fed into molten steel, it introduces CaO in the system rather than Ca. When recovery is calculated using Eq.1, this fact is not factored in the formula. Hence, the formula gives low recovery values. On the other hand, the core of pure Ca wire, whether in the form of powder or solid, has very high compactness. This prevents the oxidation of Ca in the core. As a result, the net Ca content per unit length of wire is high, so Eq.1 gives higher recovery values.

Another factor that dictates recovery is the depth of penetration of wire in the bath[3,5]. In the case of conventional wire, steel casing melts and filler material is released close to bath surface, much before penetrating deep into the bath, resulting in loss of Ca to the atmosphere due to its high vapour pressure. This leads to low recovery in conventional wire. However, owing to superior design, pure Ca wire goes much deep into the ladle compared to conventional wire. As a result, the Ca is released at such a depth from the bath surface that the resulting residence time is high. The depths at which ferro-static pressure is higher than the vapour pressure of calcium, the loss of Ca due to burning at the top of a ladle is minimised, which increases recovery. Mathematically, this depth is given by Eq. 2 (Fig. 1).

$$Ferrostatic\ pressure > vapour\ pressure\ of\ Ca$$

$$h\rho g > vapour\ pressure\ of\ Ca \qquad Eq.2$$

$$h * 7000\frac{kg}{m^3} * 9.8\frac{m}{s^2} > vapour\ pressure\ of\ Ca$$

Vapour pressure of Ca at different steel making temperatures is given in Table 4.

Table 4: Vapour pressure of Ca at steelmaking temperatures

Temperature (°C)	**Vapour pressure (atm)**	**Vapour pressure (N/m^2)**
1550	1.05	106391
1575	1.40	141855
1600	1.81	183398

At 1575°C,

$$h * 7000\frac{kg}{m^3} * 9.8\frac{m}{s^2} > 141855\frac{N}{m^2}$$

$$h > 2.06\ m$$

At 1600°C,

$$h * 7000\frac{kg}{m^3} * 9.8\frac{m}{s^2} > 183398\frac{N}{m^2}$$

$$h > 2.67\ m$$

Therefore, at an operating temperature of 1575°C, the wire should go more than 2.06 m deep in the ladle from the bath surface for ferro-static pressure to be greater than the vapour pressure of Ca. This depth at 1600°C is 2.67 m. It should be noted that the minimum depth of penetration is independent of ladle capacity.

Wire consumption

Wire consumption is indirectly proportional to recovery. If recovery is high, less wire is needed to be fed into the bath to achieve a certain level of dissolved Ca. This is the case with pure Ca wire.

Recovery of conventional wire is poor due to two factors: oxidation and evaporation. Although on paper, the Ca content per meter wire is the same for conventional wire and pure Ca wire (i.e., 68 gm/m and 69 gm/m respectively); practically, at the time of application, this value is much lower than the theoretical value for conventional wire due to substantial Ca loss because of oxidation over the period of transportation and storage. Moreover, Ca loss also occurs due to evaporation of Ca in the upper part of the ladle, i.e., near bath surface, due to premature melting of conventional wire. Therefore, the actual amount of elemental Ca that contributes in secondary refining by injecting one meter of conventional wire is far less than the theoretical value. This increases the total amount of Ca to be injected in the bath, thus the total length of wire to be injected also increases.

However, this is not the case with pure Ca wire. As discussed before, owing to high compactness and deep penetrating ability, Ca loss because of oxidation and evaporation is very low. Consequently, the actual amount of elemental Ca that contributes in secondary refining by injecting one meter of pure Ca wire is not very far from the theoretical value. As a result, the total amount of Ca to be injected in the bath is far less compared to conventional wire. Hence, the total length of wire to be injected also decreases.

Wire consumption figures in length and Ca consumption of the two types of wires for different grades are given in Table 5. From the table, it is evident that in all the cases, wire consumption decreased to more than half during the trials.

Table 5: Comparison of wire consumption of conventional wire with pure Ca wire

Grade	**CaSi/CaFe**			**Supplier#2**		
	Length (m)	Filler (kg)	Ca (kg)	Length (m)	Filler (kg)	Ca (kg)
EWNR	360	83	25	150	10.00	9.90
SAE1006 (CAQ)	320	74	22	150	10.00	9.90
SAE1008 (CAQ)	340	78	23	140	9.52	9.42
SAE1010 Alk	1000	230	69	370	25.16	24.9
SAE1018 Alk	1000	230	69	280	19.00	18.81
Sail Tower Alk	1000	230	69	332	22.57	22.35

Treatment time

Pure Ca wire affects LF treatment time in two ways. As pure Ca wire is fed at a lower feeding rate compared to conventional wires, it has the tendency of prolonging secondary refining time. On the other hand, less pure Ca wire requirement for achieving the same level of Ca in the bath has the tendency of reducing secondary refining time.

From the plant trials, it has been found that the net effect was a reduction in secondary refining time as the effect of less wire consumption outweighed the effect of low feeding rate. Time saving in the case of Alk grades is more appreciable compared to Al-treated semi killed grades, as shown in Table 6.

The effect of any cored wire on secondary refining time is calculated as follows:

$$Cored\ wire\ treatment\ time = \frac{length\ of\ wire\ required}{feeding\ rate}$$

Table 6: Comparison of wire feeding time of conventional wire with pure Ca wire

Grade	CaSi/CaFe	Supplier#1	Supplier#2	Supplier#3
EWNR	1.44	1.12	1.20	1.28
SAE1006 (CAQ)	1.28	1.20	1.20	1.44
SAE1008 (CAQ)	1.36	1.20	1.12	1.36
SAE1010 Alk	4.00		2.96	3.04
SAE1018 Alk	4.00		2.24	3.12
Sail Tower Alk	4.00		2.66	2.88

In the table, the effect of wire breakage on cored wire treatment time is not factored in. On taking into account the time expended in dealing with wire breakage, the cored wire treatment time for conventional wire in Table 6 would be even higher. Therefore, the actual time saving by using pure Ca wire is more than what is depicted in the table.

Here, it should be noted that the length of wire required is a function of its linear weight. Therefore, the length required would be less for thicker wires, which may result in further reduction in treatment time.

Consistency

At first glance of Fig. 4, it may appear that the degree of inconsistency is more in the recovery values obtained from pure Ca wire due to its higher SD compared to that of conventional wire. However, statistically, this is not true. The SD is used when we want to measure the spread of data points in a single dataset. When it comes to compare the spread between two different datasets, the parameter 'the coefficient of variation (CV)' is used. This parameter is also known as 'relative standard deviation (RSD)'. The coefficient of variation is defined as follows:

$$CV = \frac{SD}{mean} * 100$$

When two datasets are compared, the dataset with lower CV is better in terms of consistency. In the present case, the recovery values of the base dataset and those of the experimental dataset constitute the two datasets to be compared. The CV of the base dataset recovery values is

$$CV_{base} = \frac{3.02}{4.36} * 100 = 69\ \%$$

The CV of the experimental dataset recovery values is

$$CV_{exp.} = \frac{8.00}{19.06} * 100 = 42\ \%$$

From the above calculations we can say that the recovery values obtained from the pure Ca wire trials are more consistent than the recovery values obtained by using conventional wire.

Further calculations showed that the consistency of pure Ca wire was even better when only Alk steel grades were considered, with the recovery values having a CV of 31 % only compared to 41 % in the case of Alk grades made from conventional wire.

4.0 CONCLUSION

The main scope of the study was to compare pure Ca wire and conventional wires on the basis of recovery and cost of Ca treatment i.e. INR/ton. From the trial data of pure Ca wire application by three different suppliers, it was found that technologically, in all the cases, pure Ca wire fared better than conventional wires in both the parameters. Besides, this type of wire outperformed conventional wires also in the form of reduced wire breakage during wire feeding, slightly reduced treatment time and reduced clogging instances at the casters. Logistically, being conducive for all grades of steel made at the SMS under consideration, the wire obviated the need of handling two different types of wire. Also, due to high compactness of calcium, it can prevent calcium from getting oxidised resulting in high storage period or high shelf life of the coil. In view of the above, the wire proved to be a promising alternative to CaSi/CaFe under the shop's operating conditions.

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