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Statistical Analysis of Dross Data for Hydro Aluminium Casthouses

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Abstract

Reducing the formation of dross is important for a sound economic result in aluminium casthouses. In order to reduce the amount of dross the main drivers affecting the dross creation need to be identified. The first step towards identifying these drivers is to measure the dross amount on a charge basis. With a sufficiently large data set it is possible to apply statistical methods to correlate different process variables and the dross amounts. It is also possible to rank the different variables and identify those that are the most important for dross formation. In this paper multivariate statistical analysis is used to correlate the various input variables and dross formation on a charge basis and to identify the most important drivers for dross formation.

Examples from two remelt extrusion ingot casthouses and a primary extrusion ingot casthouse are given and discussed.

Introduction

Dross is a term used to define the mixture of oxides (principally Al_2O_3) and metallic aluminium that forms on the surface of molten aluminium when in contact with oxygen. Dross formation is primarily an oxidation process leading to the formation of aluminium oxide. This causes a loss of aluminium. In addition, metallic aluminium is entrained in the oxide, giving a higher metal loss.

As a part of the production process dross is removed from both the top of the furnace and sometimes from the bottom (when the furnace is empty) by dragging the dross out of the furnace typically with a rake into dross bins. The dross is usually then treated in some manner to prevent further oxidation of the metallic portion.

In all aluminium casthouses the amount of dross generated per charge should be one of the key operational parameters followed up. The dross production should be monitored (e.g. by SPC charts) since dross represents a considerable cost to a casthouse (one of the three or four top costs). The cost of dross arises from reduced metal yield, increased furnace energy consumption, increased furnace cycle time and the cost of reprocessing or conversion of the dross.

The amount of dross generated is normally expressed as the specific dross amount in % (dross weight/input weight). The amount of dross generated depends on many furnace operational aspects and it is difficult to give an exact figure as to what is an acceptable or unacceptable level. Primary casthouses producing low Mg alloys (<5 wt%) with good operational control can have dross levels less than 1%; remelt casthouses should expect higher levels of dross but once the amount of dross is greater than 4-5% great attention should be paid to the furnace operations.

Dross management is not only the measurement and follow up of dross amounts, but also understanding how dross is formed and attempting to control the furnace processes to minimize the amount of dross created.

In this paper statistical methods have been employed to analyse a large amount of real process data from three casthouses, two remelters and one primary casthouse, to further the understanding of dross production and input material types.

Statistical method

Preferably, analysis of a physical system should be done using proper physical models that realistically describe the system over the full range of the variable values. In operation, however, one usually strives for stability. Variable values are limited to a fairly narrow range because deviations are quenched before they are allowed to develop. Frequently, therefore, most non-linear physical models can be well approximated by linear models. In this study we have therefore chosen to use linear regression analysis. The advantage is that the tools and statistics for this method are easily available, even for a fairly large number of variables. The dross amount was the Y variable and all the other selected variables served as X values in a multiple linear regression analysis.

Another problem with operational data is that frequently variables are inter-correlated, and it may therefore be difficult to separate the effect of one from another. In this study, the correlations between all variables were studied by generating a correlation matrix, and care was taken to limit the use of inter-correlated variables simultaneously in the regression analysis.

The Analysis of Variance (ANOVA) approach [1] has been used as the statistical method to rate the significance of the effects of numerous variables on the dross formation.

The regression analysis was mainly made using Excel, but Unscrambler [2] was used for some of the larger initial datasets.

Data collection and data treatment

Hydro Aluminium uses a central database to collect a large amount of process parameters from its casthouses. Data from this database were used in the study. The data cover a vast amount of variables (process parameters), such as specification of additions to the furnaces, times of additions, cycle time data, and dross amounts, etc. Not every casthouse reports the same data, so an individual treatment of data from each casthouse was necessary.

Relevant data for this study are available from the end of 2009, providing data for several thousand charges. Thus, even though the data may be quite scattered, as is the case for dross amounts, significant information can be extracted by using the large data sets and proper statistical methods.

Data from one primary casthouse and two remelt casthouses were used. Considerable pre-treatment of the data before using them in the statistical analysis was required for all three data sets. This was a stepwise procedure. Firstly, to limit the number of variables, it was decided that only those that might have an effect on the dross amount should be included. This means that the variables should describe a property that, at least in theory, could cause or limit dross formation. Consequently, variables describing events or properties that follow the actual dross formation, such as scrap amounts following casting, were not included, even though in some cases they may have been correlated with the dross formation. Secondly, erroneous data (missing data, obviously wrong entries, etc.) were removed from the sets.

Results

Remelter A:

Remelter A produces extrusion ingots in many different alloys. The casthouse recycles several types of scrap, of which some can be categorised as clean and others as dirty. Dirty scrap may loosely be described as painted, coated, anodised, post consumed scrap, etc. In addition to scrap, alloying elements and a significant amount of primary Al is also added in the form of ingots or sows. There is also some internal recycling of e.g. sawing chips, drainage, and a molten heel remaining in the furnace from the previous charge. The amounts and balance of the various additions can vary considerably from charge to charge.

Dross data for more than 4400 charges were available for remelter A. After some data cleaning, dross amounts for nearly 4000 charges were available for the regression analysis. The goal of the regression analysis was to quantify the effect of the various additions and other relevant charge variables on the dross amount, i.e. to determine their specific dross forming potential (e.g. % dross per % addition). Initially all relevant variables were included in the regression analysis, without considering any inter-correlations between the variables. This included all variables containing information about additions to the furnace and the length and starting date of the melting cycle. The latter variable was included to check for any time dependence of the dross amount.

Several regression models were made and their ANOVAs analysed to make sure that inter-correlations did not confuse the conclusion. Variables with low P-values and wide confidence intervals were considered irrelevant for dross formation. In the end, only time and most of the different input materials were left. It was possible to achieve a significant differentiation between most of the various additions to the furnace. The ANOVA for the final data set is given in Table 1.

The coefficients in Table 1 give the following equation for the dross amount

$$\begin{aligned}\text{Dross (\%)} = {} & 0.78 \\ & - 0.00073\cdot\text{Days since Jan 6 2010} \\ & + 0.0067\cdot\text{\% Clean scrap} \\ & + 0.064\cdot\text{\% Dirty scrap type 1} \\ & + 0.043\cdot\text{\% Dirty scrap type 2} \\ & + 0.029\cdot\text{\% Other scrap}\end{aligned} \qquad (1)$$

In other words, for every 1% extra of dirty scrap type 1, the dross amount is expected to increase by 0.064%. For the clean scrap the increase is only 0.0067%. The average daily decrease in dross is 0.0007 %, indicating a continuous improvement in the furnace operation. The time dependence is illustrated in Figure 1. Since the main input material in addition to the scrap types listed in Equation 1 is primary metal, the intercept, 0.78%, can be interpreted as the % dross expected for a 100% primary metal charge on Jan 6 2010.

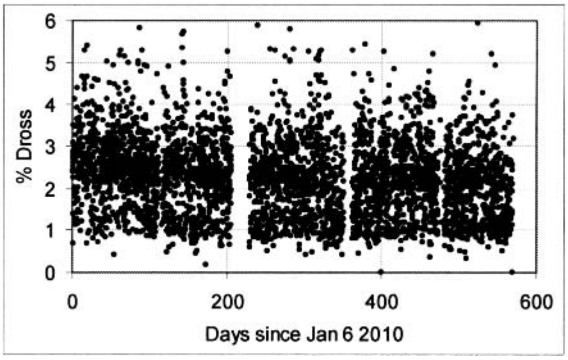

Figure 1: Dross % as a function of days since Jan 6 2010 for remelter A.

As seen in Table 1, the correlation coefficient, r, for Equation 1 is only 0.50. This is too low to give an acceptable prediction of the real dross amount for a charge, but it does not mean that the variables listed in Table 1 and Equation 1 are insignificant. On the contrary, they are highly significant, as demonstrated by the low P-values and the relatively tight confidence intervals shown in Table 1. However, since the correlation coefficient is only 0.50, there are clearly variables not included in the data set that contribute to the variation of the dross formation. Information about operator specific actions, burner operation and more scrap information (e.g. type and amount of contamination or coating, degree of shredding, etc.) could improve the dross model.

Table 1: ANOVA from the regression analysis from remelter A. Additions to the furnace are given in % of the total charge weight. 90% and 95% confidence intervals for the coefficients are included.

Regression Statistics		ANOVA	*df*	*SS*	*MS*	*F*	*Significance F*
Multiple R	0.500	Regression	5	861.7	172.3	264.2	1.9E-244
R Square	0.250	Residual	3969	2588.7	0.7		
Adjusted R Square	0.249	Total	3974	3450.4			
Standard Error	0.808						
Observations	3975						

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 90.0%*	*Upper 90.0%*
Intercept	7.82E-01	1.24E-01	6.33E+00	2.79E-10	5.40E-01	1.02E+00	5.79E-01	9.86E-01
Days since Jan 6 2011	-7.25E-04	8.13E-05	-8.91E+00	7.33E-19	-8.85E-04	-5.66E-04	-8.59E-04	-5.91E-04
% Clean scrap	6.73E-03	1.34E-03	5.02E+00	5.50E-07	4.10E-03	9.37E-03	4.53E-03	8.94E-03
% Dirty scrap type 1	6.42E-02	4.27E-03	1.50E+01	1.32E-49	5.58E-02	7.26E-02	5.71E-02	7.12E-02
% Dirty scrap type 2	4.33E-02	2.71E-03	1.60E+01	9.25E-56	3.80E-02	4.87E-02	3.89E-02	4.78E-02
% Scrap other	2.94E-02	3.03E-03	9.70E+00	5.32E-22	2.34E-02	3.53E-02	2.44E-02	3.44E-02

Remelter B

Remelter B operates in much the same way as remelter A. Fairly clean scrap is the main addition to the furnace. Primary metal and the alloying elements are also added. Then there are some dirtier scrap types.

For remelter B, it was necessary to adapt the data sets to the type of skimming performed. For every charge the top of the molten metal is skimmed to remove the dross (to increase the heat transfer and quality of the charge), while when necessary the empty furnace is also bottom skimmed. Thus, the dross amount reported for a charge may be top dross only or the sum of top and bottom dross. To complicate matters even more, the bottom dross may be accumulated over several charges. From the database entries alone, it is not possible to match the bottom dross data to a specific charge. Several ways to overcome this problem were considered, and in the end the best approach was to simply discard all charges with a high amount of dross, the reason being that combined top and bottom dross amounts will be larger than top dross amounts alone, as illustrated by the bimodal distribution shown in Figure 3. The dross amounts to be analysed were therefore from the remaining 1093 charges with top skimming alone.

Unfortunately, there was a considerable overlap in the dross amounts between top only and the combined top and bottom skimming (see Figure 3). Simply removing all charges with a dross amount higher than a certain limit, in this case 2.2%, therefore leads to removal of some of the high dross amounts from the top skimming only charges and inclusion of some of the low dross amounts from combined top and bottom skimming charges. This is in no way optimal for the quantitative study of dross forming variables. Still, since the number of charges is very high, significant results were achieved.

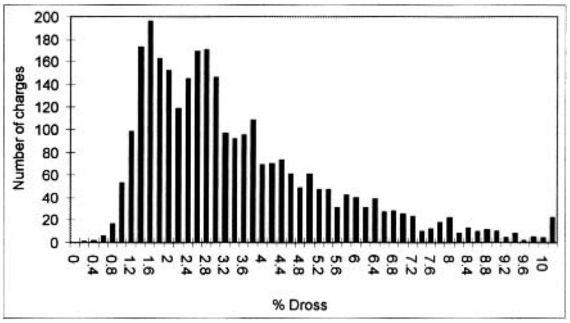

Figure 3. Histogram of dross amounts from 2924 charges from Remelter B. The distribution appears bimodal, with a split at approximately 2.2% dross.

The regression analysis was performed in the same way as for remelter A. Based on the different P-values and the confidence intervals obtained, it was found that the only significant variables of the 24 studied was the amount of the dirty scrap types, and the time. The resulting ANOVA is shown in Table 2. It is seen that the correlation coefficient, r, is 0.28 for the three variable model, which is only slightly lower than r = 0.31 for the initial 24 variable model. Removing the majority of the variables did therefore not make the model much worse.

The coefficients in Table 2 give the following linear model for Remelter B:

$$\begin{aligned}\text{Dross (\%)} = \; & 1.51\\ & - 0.00042 \cdot \text{Days since Dec 29 2009}\\ & + 0.019 \cdot \text{\% Dirty scrap type 1}\\ & + 0.012 \cdot \text{\% Dirty scrap type 3}\end{aligned} \qquad (2)$$

Table 2: ANOVA from regression analysis from remelter B using the number of days since Dec 29 2009 and percentage of dirty scrap types as variables. Additions to the furnace are given in % of the total charge weight. 90% and 95% confidence intervals for the coefficients are included.

Regression Statistics		ANOVA	*df*	*SS*	*MS*	*F*	*Significance F*
Multiple R	0.284	Regression	3	16.8	5.6	31.8	1.0E-19
R Square	0.081	Residual	1089	191.6	0.2		
Adjusted R Square	0.078	Total	1092	208.4			
Standard Error	0.419						
Observations	1093						

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 90.0%*	*Upper 90.0%*
Intercept	1.51E+00	3.54E-02	4.27E+01	7.03E-235	1.44E+00	1.58E+00	1.45E+00	1.57E+00
Days since Dec 29 2009	-4.22E-04	9.83E-05	-4.29E+00	1.96E-05	-6.15E-04	-2.29E-04	-5.83E-04	-2.60E-04
% Dirty scrap type 1	1.85E-02	4.64E-03	3.98E+00	7.24E-05	9.37E-03	2.76E-02	1.08E-02	2.61E-02
% Dirty scrap type 3	1.19E-02	3.08E-03	3.86E+00	1.20E-04	5.84E-03	1.79E-02	6.81E-03	1.70E-02

Table 2 shows that the 90% confidence intervals for the Dirty scrap type 1 and Dirty scrap type 3 coefficients are well overlapping. It can therefore be argued that the specific dross contributions for the two types are not significantly different. In that case, they should be treated as one type of scrap, e.g. dirty scrap. A single variable model was therefore made, using the sum of the dirty scrap types as the only variable. The correlation coefficient for this two-variable model is 0.28, the same as the previous three-variable model. The model is expressed as:

$$\text{Dross (\%)} = 1.51 - 0.00042 \cdot \text{Days since Dec 29 2009} + 0.0144 \cdot \text{\% Dirty scrap} \qquad (3)$$

Neither Equation 2 nor Equation 3 provides anywhere near an adequate description of the true dross formation for remelter B. They merely describe the isolated effects of the dirty scrap and time. As for remelter A, there are obviously variables not included in the data set that contribute to the variation in the dross formation. Also important is the mentioned missing information about top and bottom skimming for remelter B.

Primary casthouse

The operation of a primary extrusion ingot casthouse furnace is significantly different from the remelters' furnace operation. Most of the input material is purified liquid metal from a smelter, and the balance is high quality primary metal in the form of ingots/T-bars or sows. Some scrap, such as clean profile scrap and saw chips from the ingot cutting, is also added. The dross amount is therefore lower, as illustrated by the dross histogram in Figure 4. It is seen that the average amount of dross is close to 1%. For the remelters it is more than 2%.

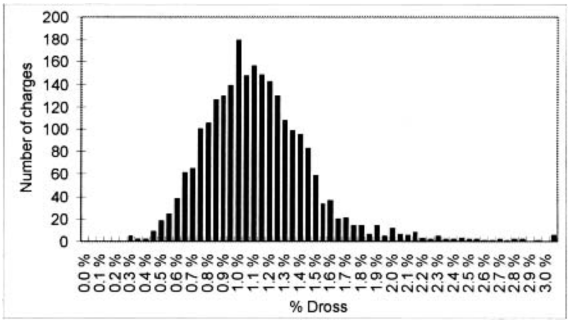

Figure 4: Dross histogram of all 1820 charges for the primary casthouse.

Dross data for 1820 charges were available for the primary casthouse. In the database the input materials to the furnace were divided into liquid metal, heel, cold metal and saw chips. Burner operation information such as energy input and firing time was also available, as were the charge cycle time, furnace number, specification of alloy produced and production shift number.

For the first regression analysis of this data set all the variables listed above were included (13 in total). The correlation coefficient was only r = 0.23 and most of the variables did not contribute significantly to the dross amount. Neither the furnace additions, specific energy use (kWh/metric t), firing time, furnace number, alloy specification nor shift number contributed significantly to the dross formation. These were left out of the second regression analysis, leaving only the most significant contributions, i.e. the total charge weight, the furnace cycle time and the amount of molten heel remaining in the furnace before the charge. The ANOVA for this regression is shown in Table 3.

Table 3: ANOVA from the regression analysis from the primary casthouse. Additions to the furnace are given in % of the total charge weight. 90% confidence intervals for the coefficients are included.

Regression Statistics		ANOVA	*df*	*SS*	*MS*	*F*	*Significance F*
Multiple R	0.186	Regression	4	8.1	2.0	16.3	3.7E-13
R Square	0.035	Residual	1815	225.0	0.1		
Adjusted R Square	0.033	Total	1819	233.1			
Standard Error	0.352						
Observations	1820						

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 90.0%*	*Upper 90.0%*
Intercept	1.38E+00	8.28E-02	1.67E+01	3.22E-58	1.22E+00	1.54E+00	1.24E+00	1.52E+00
Days since Jan 10 2011	-5.33E-04	1.89E-04	-2.82E+00	4.91E-03	-9.05E-04	-1.62E-04	-8.45E-04	-2.22E-04
Cycle time (hr)	1.97E-02	4.26E-03	4.62E+00	4.06E-06	1.13E-02	2.80E-02	1.27E-02	2.67E-02
% Molten heel	1.14E-02	2.15E-03	5.30E+00	1.28E-07	7.17E-03	1.56E-02	7.85E-03	1.49E-02
Charge weight (kg)	-7.88E-06	1.45E-06	-5.43E+00	6.44E-08	-1.07E-05	-5.03E-06	-1.03E-05	-5.49E-06

From Table 3, the equation for the dross can be extracted:

$$\begin{aligned}\text{Dross (\%)} = \; & 1.38 \\ & - 0.00053\cdot\text{Days since Jan 10 2011} \\ & + 0.020\cdot\text{Cycle time (hr)} + \\ & + 0.011\cdot\text{\% Molten heel} + \\ & - 7.9\cdot 10^{-6}\cdot\text{Charge weight (kg)} \qquad (4)\end{aligned}$$

The dross amount increase with cycle time is partly due to the simple fact that dross is formed as long as the metal is in the liquid state, but equally important may be the fact that the cycle time also is correlated with the fraction of cold metal and firing time (burner energy input). Longer time as liquid and more burner firing (energy input) before casting is likely to give more dross. The dross contribution from the charge weight is probably due to the reduced surface to volume ratio with increasing charge weight since the surface area of the molten bath is more or less independent of charge weight. If it is assumed that the dross formation mainly takes place on the surface of the molten bath, a large charge weight is beneficial. The contribution of the molten heel to the dross amount is harder to explain.

The cycle time and the charge weight are fairly strongly correlated (r = 0.31). It can therefore be questioned whether both should be included in the regression. However, removing either variable reduces the correlation coefficient considerably, so both variables were used in Equation 4.

Again the correlation coefficient for the regression, r = 0.19, is very low. Equation 4 has therefore no predictive capability, but still describes significant contributions to the dross amount. To improve the equation, other variables not present in the database must be added. It is not obvious which ones, but how the skimming is performed, temperature at skimming, stirring procedures, burner air/fuel ratio, and more information about the additions may help.

Discussion

The main results of the present study can briefly be summarised as follows: For the remelters, the dross amount depends mainly on the input materials. Clean additions, such as primary metal and clean scrap, have low specific dross formation. Dirty scrap types have high specific dross formation. For the primary casthouse no significant differences between the specific dross contributions of the cold metal additions were found. The reason is probably that the additions are mainly clean. The main drivers for dross were found to be the charge cycle time, the amount of molten heel and the total charge weight. In addition to the contributions from the input materials, a general improvement with time was seen for all three casthouses. This is interpreted as the result of the continuous improvement programmes taking place in the casthouses.

No alloying elements were found to contribute significantly to dross, neither for the remelters nor for the primary casthouse. Although Mg is know to have an effect on the amount of dross (increased Mg content give increasingly higher dross amounts) [3] and [4], the lack of a correlation here is not surprising as the typical Mg level in the alloys produced in all casthouses is between 0.3wt% and 1 wt%.

The present statistical analysis gave a much better differentiation between the various types of scrap for remelter A than for remelter B. The reason is most likely the aforementioned missing information in the database about the special dross routine applied at remelter B, which introduces considerable mismatch between the dross amount numbers and the other charge variables. It is therefore assumed that the quantification of the specific dross contributions of the various types of scrap, Equation 1, gives a more correct picture than Equations 2 and 3.

Since many variables are hard to quantify, an adequate predictive model for dross formation may be difficult to obtain.

Conclusion

Statistical analyses of casthouse furnace charge variables such as amounts of input materials, furnace cycle time, date of charge, energy load, etc. have been made to determine the variables' quantitative effect on the charge dross formation. Data for three casthouses, i.e. two remelters and one primary casthouse, were collected from Hydro's central database. Data for more than one thousand charges from each casthouse covering the last one to two years were used in multivariate linear regression analysis. The large data sets enabled proper statistical analyses.

The main conclusions are as follows:

- The obtained linear regression models for the casthouses do not give complete descriptions of the dross amount for a charge. Process variables in addition to those available in the database are required to improve the models. However, clearly significant quantitative effects of many of the available variables could still be estimated.
- For the remelters, the dross amount depends mainly on the input materials. Clean additions, such as primary metal and clean scrap, have low specific dross formation. Dirty materials have high specific dross formation.
- For the primary casthouse no significant differences between the specific dross contributions of the different cold metal additions were found. The drivers for dross identified were the charge cycle time, the amount of molten heel from the previous charge and the total charge weight.
- A general reduction of dross amount with time was seen for all three casthouses. This is interpreted as the result of continuous improvement programmes.
- None of the alloying elements were found to contribute significantly to dross, neither for the remelters nor for the primary casthouse.
- Improving the dross models to a level where they can reach predictive ability requires more information about each charge. Such information may be a better description of the additives, e.g. the type of surface treatment of the scrap, its specific surface area (e.g. m^2/kg), thickness of anodic and lacquered layers, amount of contamination etc. More quantitative information about furnace operation may also be necessary. Burner operation, air/fuel ratios and skimming tools used can also contribute to the dross formation. However, operating variables difficult to quantify may also be important. Examples are operator actions: how the cold metal input materials are positioned in the furnace, how the melt is mixed, and if the sidewall dross is removed in the same way every time.

References

1. See e.g. G.E.P. Box, W.G. Hunter and J.S Hunter, *Statistics for Experimenters*, J. Wiley & Sons, 1978.
2. http://www.camo.com/.
3. J.A. Taylor, *Oxidation, dross and melt loss issues involved in the aluminium casthouse*, Aluminium Casthouse Technology, Australia, ed. J.F. Grandfield, J.A. Taylor, (2007).
4. W. Stevens, G. Riverin, V. Goutieres and J-Y Fortin, *Aluminium melting and dross formation – a historical and modern perspective of the situation*, Light Metals 2003, Ed. P.N. Crepeau, TMS 2003, p. 801.
5. D. Dispinar, A. Kvithyld and A. Nordmark, *Quality assessment of recycled aluminium*, Light Metals 2011, Ed. S.J. Lindsay, TMS 2011, p. 731.