Light Metals 2014
Edited by: John Grandfield
TMS (The Minerals, Metals & Materials Society), 2014

CONCEPT AND DESIGN OF DUBAL POT START-UP FUSES

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Keywords: Cell start-up fuses, Aluminium reduction cells, Modeling, DX technology, DX+ technology

Abstract

Before start-up, aluminium reduction pots are connected together by short circuiting the cathode busbars of two adjacent pots. Most of DUBAL pot technologies use aluminium wedges for this purpose. At pot start-up these wedges are removed with wedge pullers. To minimize electrical arcing during removal of the wedges, DUBAL uses specially designed start-up fuses which are made of aluminium plates and connected in parallel with the wedges. The cross section of fuses is chosen so as to stay connected while the wedges are inserted and to break shortly after disconnecting the wedges. DX and DX+ pot technologies use welded fuses for potline start-up and clamped fuses for pot re-starts due to practical considerations. In this paper, the concept and design of these fuses is presented along with industrial trials and design validation. Comprehensive 3D modeling of these fuses was carried out during the design process, using ANSYS software package and excel based analytical calculations.

Introduction

Lots of preparation is carried out on the pot before it is cut-in. For pots in a new potline, the wedges must be installed in a full section before the busbars can be energised. Then, the cathode flexes are connected to the collector bars, the superstructure is installed, the preheat resistor bed is prepared and anodes are installed. The pot is ready to be cut-in by removing the wedges. When a pot of an operating potline is shutdown, the first step is to install the wedges. Then, the superstructure is removed and the cathode flexes are disconnected. After the new pot is in place, the same steps are followed as in a new potline. At each of these stages, the current distribution in the wedges and busbars is different and all possibilities have to be studied in order to determine the highest load in the busbars and wedges.

When an electrical circuit is opened, such as during wedge pulling, an electrical arc develops between two separating surfaces, if the voltage drop between the open contact surfaces is large enough to sustain the arc. Arcing could damage the wedges and the wedge pockets and could have potential safety implications on people working within the pot vicinity. In order to decrease the voltage drop between the opening contact surfaces and to minimize electrical arcing during disconnection of the wedges, DUBAL uses specially designed start-up fuses which are made of aluminium plates, connected in parallel with the wedges. These are designed so to stay connected while the wedges are installed and to break or melt shortly after disconnecting the wedges. For practical reasons, DUBAL uses welded fuses for potline start-up and clamped ones for pot replacement in an operating potline.

DUBAL's initial experience with fuses during pot cut-in involved using the fuses together with shunts. For instance, the design for EMAL potline 1 and 2 start-up used fuses together with shunts since preheat was done with full bed resistor coke. For EMAL potline 3, the pot preheat is done with 100% graphite and without shunts. In this case, the pot will take full load once it is cut-in. The fuse was redesigned to take equivalent current as in potline 1 and 2 set-up and maintain a safe environment for cut-in.

In this paper, the concept and design of fuses is presented along with industrial trials and design validation. Comprehensive 3D modeling of these fuses was carried out during the design process, using ANSYS software package and analytical calculations.

Principles of Fuse Design

The principle of using start-up fuses is well known and has also been applied to pot technologies that do not use wedges for pot bypass. In [1] the fuses were used across shunt blocks on anode risers. However, the design of the fuse depends largely on the busbar technology and has to be developed for every new technology. The required time to melt the fuse (fusing time) is a design parameter that depends on the operation practices and safety considerations. Operation practices that involve manual work or people staying close to the pot when the wedges are removed or the shunt blocks are separated require longer fusing time in the order of minutes. In the case of [1], the required fusing time was 10 minutes because the shunt blocks were disconnected manually. In DUBAL, wedges are used to stop a pot, wedge extraction is automated and people involvement in this process is minimal, which allows for a shorter fusing time in the order of seconds.

Henceforth, the discussion in this paper will be limited to DUBAL technologies which use wedges to stop a pot. The fuse connects the downstream of an operating pot to the upstream of the stopped pot in parallel with the wedges. Current load in wedges is different along the pot due to specifics of busbar design. This is one reason why the tendency to arc is not equally distributed among the wedges. The fuse is most effective if it is installed near the wedge with highest current loading. However, there is also a random component in wedge pulling because there may be a slight delay between one wedge removal and another, potentially causing more arcing in the wedges that are removed last due to higher current loading. When all wedges are removed, most of the pot current flows through the fuses (some of the current goes through the pot), leading to rapid breaking or melting of the fuses.

The fuses, being in parallel with the wedges, carry some current while the wedges are connected. The cross-section of the fuses must be designed large enough to handle the loading while the wedges are connected and small enough to break the circuit quickly when the wedges are disconnected. Another important aspect of fuse design is the provision for cases when one or more of the wedges are stuck and fail to be removed. In such cases, the common operational practice in DUBAL is to put back the wedges in order to reduce the load on the stuck wedge. The fuse, in this case, should preferably stay connected for the duration required to re-install the remaining wedges, otherwise the broken fuse has to be re-installed before cut-in.

Practical considerations should be also taken into account when designing a fuse. One of these is that it is possible to weld the fuse on the busbars when there is no current in the potline (situation in potline start-up) and that it is not possible to do so when the busbars carry current (start-up of a pot in an operating potline). For pots in a new potline, the option to weld simplifies the design of the fuse. In an operating potline, the fuse has to be clamped to the busbars. Also for pot start-up in an operating potline, it is preferable to use a fuse that can be carried by operators.

ANSYS Models

To design the fuse, ANSYS finite element modeling was used. Two kinds of models were created for this purpose: a global model and a local model. The global model represents all the busbars as well as anodes and cathodes. The model starts in the metal pad of the upstream pot and ends in the metal pad of the downstream pot in a similar way as in [2]. Different stages in the cut-out were simulated:

- Wedges are in place before connecting the cathode flexes,
- When the cathode flexes are connected and
- When anodes are installed.

For the global model, ANSYS 1D link elements were used. The models were developed and validated for DX and DX+ pot technology. This model was used to evaluate the current loading of the fuse in different locations. This helped to determine the best location and size of the fuse.

Local models of the wedges and fuses were also developed in ANSYS. For that, 3D solid elements were used. The wedge models were similar to the ones in [3]. Boundary conditions for those models were obtained from the global model. The results at steady state conditions were obtained first and used later on as initial conditions for transient model runs. Transient models were used to study the impact of increasing the current loading in the fuses and wedges with time. Figure 1 shows a local fuse model.

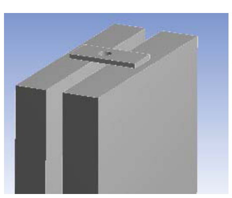

Figure 1. Local model of a welded fuse.

Contact resistances of the wedges were derived from the measured voltage drops in the wedges in DUBAL DX+ Eagle prototype pots during the start-up.

Model Results

Based on the physical limitation and the space available only a few locations were taken into consideration for the fuse. These locations were compared, using the same fuse size in each location, and the current distribution and temperatures were evaluated. The fuse location and size satisfied the criterion that the fuse does not melt when the wedges are connected. Different fuse cross sections were modelled. A fuse with bigger cross sectional area will have less current density and, thus, will have lower temperature. For DX+ pot at 440 kA, an arrangement with 2 fuses and 10 wedges was chosen. Table I shows current distribution and temperature in the wedges for welded fuses in a DX+ pot. Results are shown for half of the pot due to assumed symmetry in the model.

Table I. Current and temperature in wedges and welded fuses of DX+ pot at 440 kA.

	Current (kA)	Temperature (˚C)
Fuse 1	14.5	133
Wedge 1	52.6	106
Wedge 2	29.2	86
Wedge 3	17.8	78
Wedge 4	37.9	99
Wedge 5	60.8	112

Similarly, the clamped fuse is designed for the start-up of DX+ pots in an operating potline. Current and temperature in one half of the clamped fuses and wedges are shown in Table II, the other half is identical due to assumed symmetry in the model.

Table II. Current and temperature in wedges and clamped fuses of DX+ pot at 440 kA.

	Current (kA)	Temperature (˚C)
Fuse 1	6.6	121
Wedge 1	56.6	106
Wedge 2	31.0	87
Wedge 3	18.8	79
Wedge 4	38.3	99
Wedge 5	61.3	113

Based on these results, local models of the wedges and fuses were run. The currents entering and exiting the adjacent busbars, on which the fuses are attached, along with the temperature boundary conditions, are obtained from the global model as discussed before. These boundary conditions enable 3D modelling of the local conditions in any of the wedges or the fuse. Figure 2 shows the temperature profile in a welded fuse for DX+ pot at 440 kA using steady state analysis.

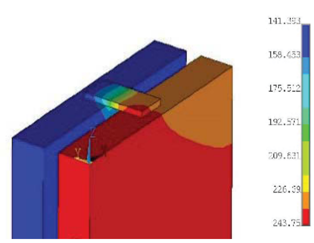

Figure 2. Steady state temperature profile in a local model of a welded fuse when all wedges are still in place.

Using ANSYS transient analysis, the local model of the fuse can be used to estimate the fusing time. In order to calculate the maximum current loading in the fuse, which occurs when the last wedge is removed, the global model was run with all the wedges removed and only the two fuses left in place. Results show that 84 % of the total current flows through the two welded fuses. For the clamped fuse case, only 73 % of the current passes through the fuses. These values were then used in the local model to calculate the temperature evolution in the fuse and the fusing time. Figure 3 shows the temperature in the fuse from the local ANSYS transient model. The melting point of fuse was assumed to be 650 °C. As can be seen from Figure 3, the fusing time is about 5 seconds for the welded fuse and about 6 seconds for the clamped fuse.

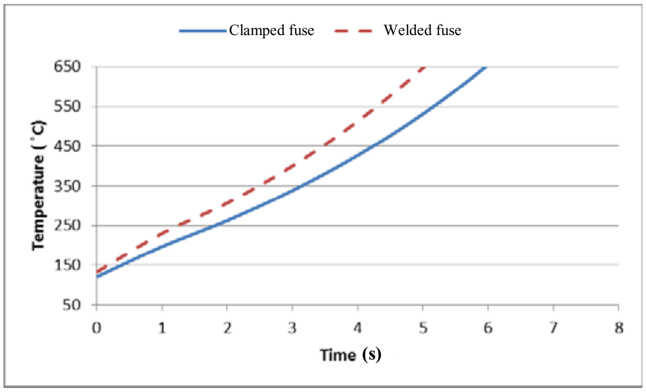

Figure 3. Temperature evolution in welded and clamped fuses for a DX+ pot at 440 kA.

An additional aspect of the fuse design is to consider the condition when one or more of the wedges fail to be removed by the extraction unit. This will redistribute the current in the wedges and increase the loading in the fuse. Different scenarios with different wedges stuck were modelled with the global model to get the current and temperature distribution in the fuse and in the remaining wedges. The worst case is when only one of the 10 wedges gets stuck. Table III below shows the current in a stuck wedge as well as in the two clamped fuses.

Table III. Current in a stuck wedge and two clamped fuses of DX+ pot at 440 kA.

	Current (kA)
Wedge 1	313
Fuse 1	16
Fuse 2	27
Total in wedge 1 and in 2 fuses	356
Current through the pot	84

The transient model of the fuse shows that fuse 2, which is far away from the stuck wedge, will melt in about 3 minutes. The current will redistribute again and the wedge will take the additional 27 kA which was taken by fuse 2. Fuse 1, which is adjacent to the wedge, will melt in about 20 minutes. The second fuse melts much later than the first one because the wedge near the second fuse takes off the load from the fuse. The temperatures in the two fuses and the stuck wedge are shown in Figure 4. The wedge temperature reaches around 500 °C in 25 minutes and would melt much later than the fuses. However, from practical point of view, the increase in wedge temperature will cause expansion of the wedge making it more difficult to be removed and possibly fusing the wedge to the busbars before it would melt.

Modelling of various scenarios helps in setting some guidelines for pot operation in case of any abnormalities. When a wedge gets stuck, the common practice is to re-install the remaining wedges. Based on these results, the pot start-up team can be informed that if a wedge gets stuck, the fuse furthest from the wedge will melt in approximately 3 minutes and the fuse neighbouring the wedge in 20 minutes. In such cases, the melted fuses would need to be replaced and safety precautions should be taken around the fuses.

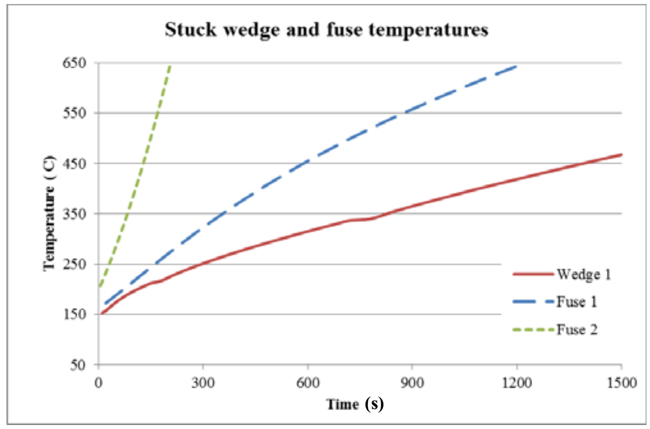

Figure 4. Temperature in fuses and in a stuck wedge for DX+ pot at 440 kA.

Model Validation

Clamped fuses

To validate model results, clamped fuses were tested in DUBAL DX pots at 385 kA. For the test, the fuse thickness of EMAL Potline 3 design was decreased proportional to the amperage. A thermocouple and two voltage probes, indicated in Figure 5, were installed on the fuses in order to monitor the temperature and the current through the fuse continuously with a data logger.


Figure 5. Clamped fuse after the trial, with indication of the position of voltage probes (pink arrows on the sides) and of the thermocouple (blue arrow in the middle).

Figure 6 shows the increase in temperature and current as wedges are being pulled out. Extraction of each wedge can be seen from the step changes of the current in the fuses. The steps in the fuse current vary depending on the number of wedges pulled and their distance from the fuse. The delay between the first and last wedge pulled was about 30 seconds. The fusing time is considered to be the time between the last wedge pulled and the breaking of the fuse. The measured fusing time is thus approximately 9 seconds. The maximum measured current through both fuses was 328 kA. This means that 57 kA was going through the anode risers to the pot at that time. Figure 6 also shows that the currents in the two fuses are not equal, which indicates some randomness in the fuse and wedge behaviour.

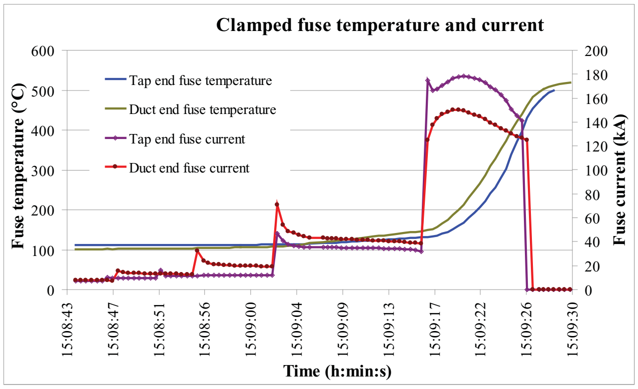

Figure 6. Measured temperature and current in the two clamped fuses in a DUBAL DX pot at 385 kA.

As can be also seen from Figure 6, the fuse temperature was 400 – 450 °C at the time of breaking, indicated by a sudden drop of current to zero. The temperature was lower than the melting temperature of 650 ˚C due to two reasons:

- The thermocouple was 60 mm away from the fuse breaking line,
- The fuse broke due to mechanical stresses and bending moment produced by thermal expansion of the arched design. This is seen in Figure 5.

Welded fuses

Welded fuses are being used in the start-up of EMAL Potline 3. As can be seen from Figure 7, welded fuses break by melting.

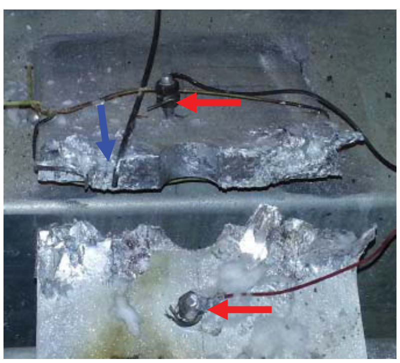

Figure 7. Welded fuse on an EMAL Potline 3 pot after breaking. Red arrows show voltage probes, blue arrow shows the thermocouple.

A thermocouple and two voltage probes were used for the validation of the welded fuse, too. The red arrows in Figure 7 show the location of the voltage probes while the blue arrow shows the location of the thermocouple. The current in the fuse was calculated from the voltage drop between the two probes and the measured temperature. The temperature and the current in the two fuses are shown in Figure 8 from just before the wedges started to be pulled to a few second after the fuses melted. The maximum temperature of the fuses was 700 – 770 ˚C which is higher than the melting point of aluminium, indicating the presence of electric arc and not just simple melting. The current in the fuses shows the delay in wedge removal between the first and last wedge of approximately 45 seconds. The fusing time, counted from the moment of last wedge removal, was about 5 seconds; which is exactly as predicted by the model, shown in Figure 3. Maximum current in both fuses was 405 kA just after the removal of all wedges, which means that 35 kA was flowing through the pot at that moment. Later, the total current in the fuses decreased to 378 kA at the moment of fuse melting, because the fuse resistance increases with temperature. However, the two fuses did not react identically, which shows some randomness in the fusing process.

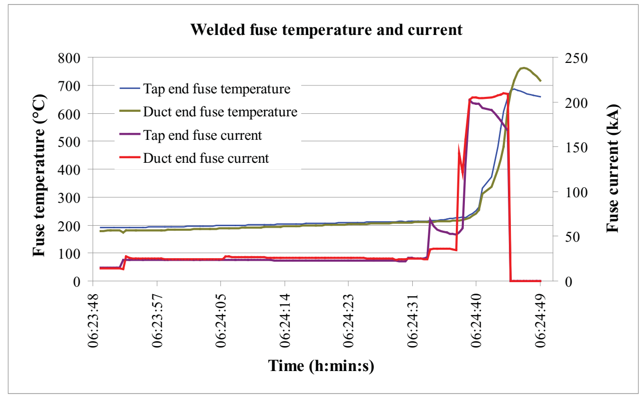

Figure 8. Measured temperature and current in the two welded fuses in an EMAL DX+ pot at 440 kA.

After the fuse breaks, it is important to ensure that no future short circuit will take place across the fuse, which might occur particularly during anode effects in cases when a fuse does not burn out as much as shown in Figure 7. The clamped fuse is easily removed right after the cut-in. For the welded fuse, a piece of wood is immediately inserted in between the two parts of the melted fuse to avoid any short circuit between them. Later on the fuses can be cut out.

Conclusions

DUBAL has successfully designed and implemented welded and clamped pot star-up fuses for DX and DX+ pot technology. Tests on operating pots showed that, as intended, the fuses do not break when wedges are connected, but they do within a few seconds after the removal of the wedges. The start-up fuses eliminate electrical arcing in the wedges during the removal with wedge pullers and also assure personnel safety during the pot cut-in. The fuses were successfully used in the star-up of EMAL DX potlines 1 and 2 pots and are being used now in the start-up of EMAL DX+ Potline 3 pots.

References

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