The Art (Science) of Bar Casting

By Ilonka Macdougall, Senior Manager - Fabrication, Quality Control, Finished Goods and Despatch, Rand Refinery Pty Ltd

This is an abridged version of the paper which was delivered at the recent LBMA A&R Conference. The purpose of this paper is to share the learnings from test work conducted at Rand Refinery to find a solution for button formation and ‘plug-like’ defects produced on London Good Delivery (LGD) bars. The aim of the test work was to ensure that production quality complied with the LBMA visual guidelines released in 2015. Button formation and ‘plug-like’ defects were a historical problem at Rand Refinery and the solution identified resulted in a 97-year practice being stopped – namely hand pouring a LGD bar.

History of Good Delivery Bars at Rand Refinery

Rand Refinery was established in 1920 in Germiston, South Africa, by the Chamber of Mines of South Africa to refine all the gold produced by South Africa’s gold mines. On 27 November 1920, Rand Refinery Ltd was registered as a private company and the building of the facilities commenced in August 1920.

The first LGD bars were produced in 1921 and, in the period since then, 51,000 tons of mined gold have been refined at Rand Refinery. The bulk of the products produced were in the form of LGD bars. Krugerrand production started in 1969, small cast bar production in 1995 and minted bar production in 2013. The current mined throughput is around 300 tons per annum and this is a decrease from approximately 1,000 tons per annum produced in the 1990s.

Based on annual outputs, Rand Refinery has produced approximately 3 million LGD bars through a manual pouring process which remained unchanged until December 2016. On average, 200 bars were poured a day using the manual pouring process.

Refinery and Fabrication Value Chain

The flow chart in figure 1 shows a high-level overview of the process flow of material received into Rand Refinery from various mines around Africa and the rest of the world. Feedstock can be received in the form of mine doré, mine concentrates, recycled material and smelter doré. Material evaluation is conducted in the melt house and, on finalisation of the mass and assay, the material is transferred to the Fine Gold department in the Refinery. All material is refined using the Miller Process. The charge make-up used in LGD bar production is important as South African Mines send through deposits which can contain iridium, palladium and other platinum group metals. Some of these metals are hard to detect and affect the surface finish of the bar. Material which contains iridium is not used for the direct production of LGD bars. This material is treated and poured into anodes which are then processed further in the Electrogold facility. Material is received from Electrogold in the form of 9999 granules and this is subsequently silvered down for the production of LGD bars to not less than 99.505% gold content.

Figure 2 illustrates a simple process flow for producing a LGD bar using the manual pouring process:

Mould preparation includes curing the mould, smoking the mould using a diesel flame, heating the mould to the required temperature on the gas flame table and finally placing the mould on the scale ready to receive the molten metal.

Material is received from the Fine Gold (a direct molten transfer) or the Grain Casting department (granules). The molten metal is sampled to confirm that the assay meets LBMA requirements. If the assay is greater than 99.99%, the molten charge will be silvered down. A 1 ton induction furnace is used and the molten charge mass is approximately 750 kg.

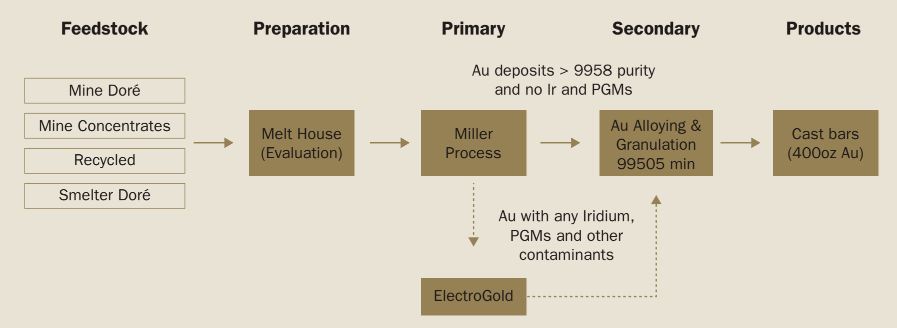

Figure 1

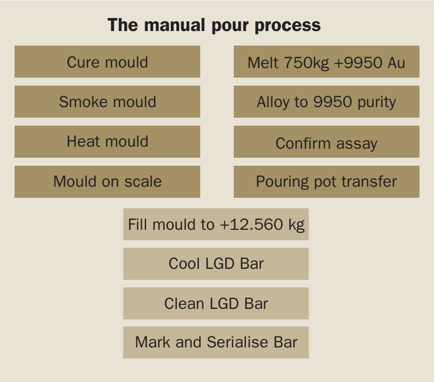

Figure 2

Molten metal is poured into a pouring pot and before being manually poured into a mould placed on a scale. Four bars are produced at a time, with a sample disc being taken after every 12 bars to verify the assay.

As soon as the molten is poured into the mould, a gas flame is used to control the cooling process until the metal has solidified. The mould is tipped into a quench tank to be cooled down, before it is serialised, cleaned, stamped with the assay and logo, weighed and then finally checked by two quality control technicians. Good bars are then transferred to the Final Storage and Despatch Department for final mass verification and preparation for shipping to the customer.

The bar casting team comprises five operators. The pouring team always work in pairs, with one person pouring and the second operator ensuring an even flow of molten metal into the mould. The other three operators are responsible for taking the moulds to the quench tank and managing the mould process.

Since this is a manual process, the ergonomics of the work space is a challenge, with the average combined mass of the mould and molten metal being approximately 25 kg.

Reasons for Investigation

In February 2016, a number of LGD bars were returned to Rand Refinery after being found to be ‘non-good’ delivery bars by a vault in London. The reasons for the rejections were cited as non-compliance with the visual guidelines, with the bars having buttons and plug-like defects. The visual guidelines were introduced by the LBMA in late 2015. It must be noted that buttons and plug-like defects were a historical defect at Rand Refinery, with at least 50% of all LGD bars produced showing this defect. Internally, there was also a problem with layering and this was a further challenge for which a solution was already being sought.

At the time, the order book for Rand Refinery was predominantly made up of LGD bars and the change in the visual guidelines therefore had a major negative impact on the business model. These included reputational damage, gold lock-up, increased costs due to rework, impact on the pouring team due to the high rework rate as well as the risk of missing customer orders. At least 5 tons of material needed to be converted weekly and, with a reject rate of greater than 60% due to zero tolerance of these defects, a solution had to be found as a matter of priority.

Looking after the health and safety of the team was also a challenge as the high reject rate demanded a high rework rate. Despite these challenges the bar casting team and associated support teams had the commitment and tenacity to overcome the challenges posed by the hard physical work involved and managed to meet the weekly order requirements.

The photograph in figure 3 shows an example of one of the returned bars with button and plug like defects.

Figure 3

The challenge for the business was to find a way to produce a bar with zero defects. A cross-functional team of 18 employees was established, with representation from the Quality Control, Technical Assurance, Laboratory, Asset Care and the bar casting team.

Rand Refinery was also fortunate in being able to liaise with peers around the world to learn from their experience and helps identify alternative solutions and best practice. The Royal Canadian Mint shared technical data on the mould dressing used, the Perth Mint on pouring practices and mould design, and Metalor on mould surfaces and design. The business made a decision that the acceptable reject rate would need to be < 5%. A plan had to be formulated in which each parameter was identified and then checked to ascertain whether or not there was a causal relationship with respect to button formation or the formation of plug-like defects.

Bar Casting Process

Figure 4 shows a more detailed map of the bar casting process. Each mould is smoked using diesel fumes for at least 36 seconds. A gas heating table is available for maintaining the temperature of the moulds should there be a breakdown or emergency. Forty-eight moulds make up a mould set. Four scales are used during the pouring process. This was the best fit for the pouring team and the way the line was set up. As soon as the last mould has been poured and the first mould molten has cooled down sufficiently to be transferred to the quench tank, a continuous process flow is established.

On pouring the molten metal into each mould, a flame is immediately put on the mould to slow down the cooling and improve the surface finish. Once the molten is solidified, the mould is transported to the quench tank using a specially designed trolley. This is to reduce some of the manual handling for the team. On emerging from the quench tank, the bar is numbered, cleaned, stamped with assay, date and logo, and the mass is verified using a double weighing system. Two Quality Control Technicians then inspect the bar on physical appearance, ensuring compliance to the LBMA visual guidelines

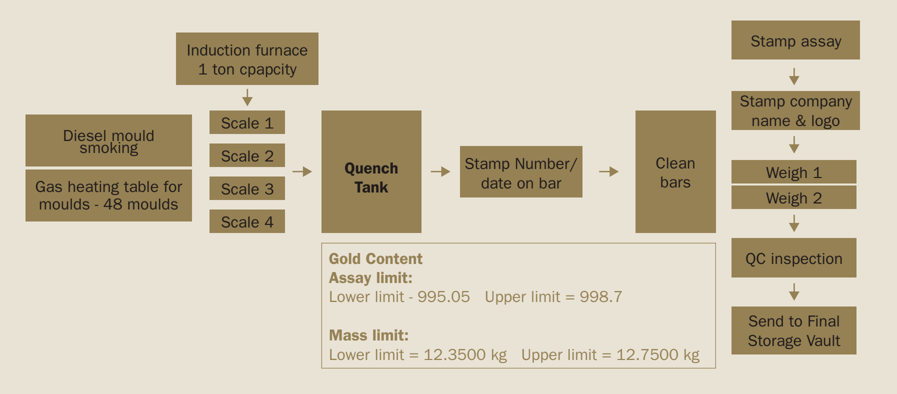

Figure 4

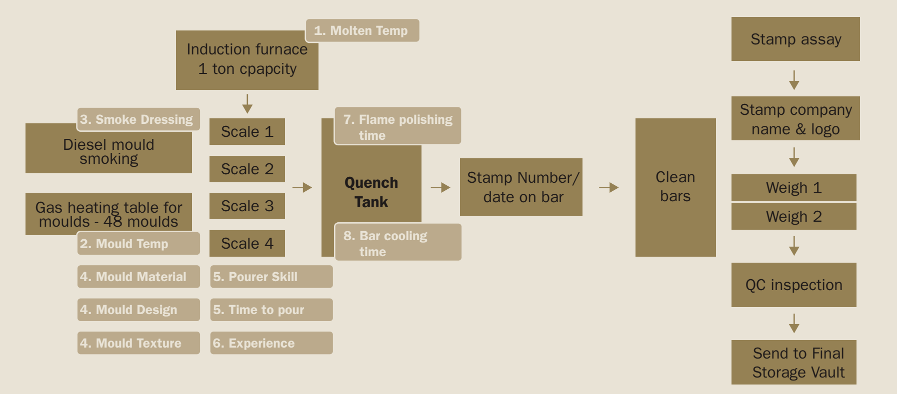

Figure 5

Process Parameters

The next step was to identify the process parameters which possibly had an effect on the formation of buttons and/or plug-like defects.

As illustrated in figure 5, the following process parameters were investigated:

- the molten metal temperature at pouring
- the mould temperature
- the mould material used and the surface texture and finish
- the hand pouring skills and experience of the operators
- time taken to pour a bar
- the experience of the operators
- the flame polishing time, and
- the time it took for the bar to cool.

It was ascertained in the early part of the investigations that the smoke dressing, flame polishing time and the bar cooling time did not have an impact on the formation of buttons or plug-like defects, and no further testing was conducted.

Impact of Molten Temperature

The next parameter that was investigated was the impact of the molten metal temperature just before pouring commenced relative to the percentage of bars rejected due to the formation of button and/or plug-like defects.

The molten metal temperature ranged from 1,100°C to 1,450°C. The blank bars referred to in chart 1, were bars produced with no buttons or 'plug-like' defects. As the molten metal temperature increased, it also became harder to manage from a health and safety perspective as the personal protective equipment (PPE) issued to the team had to meet higher specifications, which resulted in thicker material and additional risks with manual handling.

It can be seen from chart 1 that there is no real discernible correlation between the molten metal temperature on the production of a blank (good) bar versus the production of a bar with buttons and/or plug-like defects.

During this test work, it was observed that there seemed to be some kind of relationship between the temperature of the mould and the formation of buttons and/or plugs. This was mainly due to the fact that the moulds were heating up with each successive round poured and becoming harder and harder to cool down, and patterns were observed with button formations. It was decided to focus attention on the pouring technique of the operators. It was also observed that moulds with different surface finishes cooled down at different times.

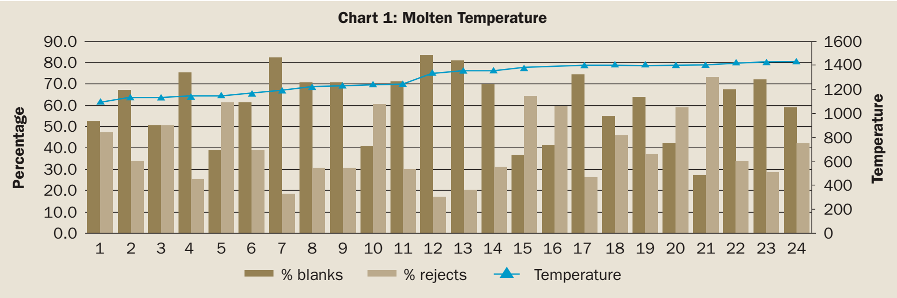

Chart 1: Molten Temperature

Experience of Pourers

In this exercise, data was collected over a one-month period to identify whether or not the pouring technique and experience of the pourers was a contributing factor to producing bars with buttons or plug-like defects. Three pourers with different levels of experience were monitored. The first pourer had more than ten years of experience, the second had more than three years whilst the third had less than one year.

The same mould set and consumables were used and different pouring techniques were also tried.

The percentage of good bars produced by all three operators, regardless of the pouring technique used, was between 60% and 63%. It was deemed reasonable to conclude that the experience of the pourers was not a contributing factor to the production of bars with buttons and plug-like defects.

Chart 2 illustrates the outcome of the tests.

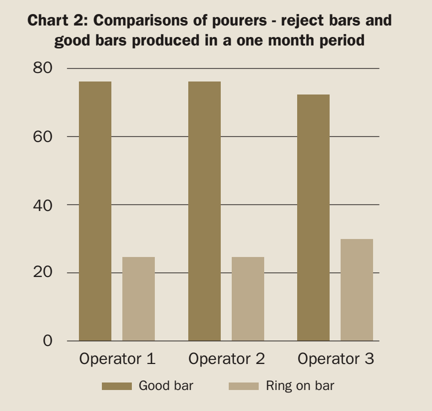

Chart 2: Comparisons of pourers - reject bars and good bars produced in a one month period

Mould Surface

In the first month of testing, it became clear that the mould surface finish was having a major impact on whether or not a bar was produced with buttons and plug-like defects. The moulds were of a mild steel composition and all moulds were purchased from the same local foundry. Historically, Rand Refinery purchased moulds with a smooth surface finish. However, due to the increase in demand, moulds with a rough surface finish had also been introduced into the mould set due to a delay on the order from the supplier. The bulk of the moulds received from the supplier for this batch were rejected due to the rough surface finish and only a handful were available on the floor for use. It was noted that all the bars produced with the rough surface finish mould had a 20% reject rate. The moulds with a smooth surface finish had an average of 50% bar production with buttons and/or plug-like defects.

Based on this data, an order was placed for a full set of moulds with a rough surface finish – the same finish as the moulds that had originally been rejected. Unfortunately, due to changes in the foundry's finishing process, moulds with the rough surface finish could no longer be replicated. The best that could be offered to the business were moulds with a sand-blasted finish – this was not as rough as what was requested, but it was approved and the order placed.

The smooth, rough and sand-blasted finish moulds were all subject to the same initial curing process using castor oil and gas flame before being introduced into the bar casting production process.

In chart 3 it can be seen that, on average, the sand-blasted finish moulds had a reject rate of 23% bar production with buttons or plug-like defects.

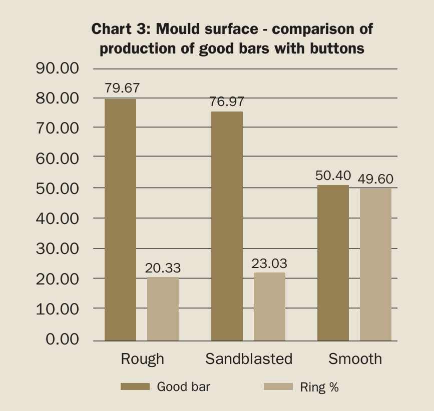

Chart 3: Mould surface - comparison of production of good bars with buttons

The next step was to identify, in more detail, what process parameters needed to be controlled to consistently produce bars at a reject rate of less than 25%, with the target being less than 10% per batch.

Temperature of the moulds during the pouring process

The graphs in chart 4 indicate test work conducted where the percentage of reject bars produced was recorded relative to the temperature of the mould at the time of pouring.

The moulds with the rough surface finish produced reject bars at less than 5% when the moulds were at room temperature. Since this mould finish could no longer be sourced, it was a moot point.

The moulds with the sand-blasted finish produced the highest rate of good bars in the range of 100°C to 200°C. The reject rate was highest between 50°C to 100°C.

The moulds with a smooth surface finish only started producing a lower reject rate at temperatures of above 300°C. Working with moulds and molten at such high temperatures had a number of challenges. These ranged from the increased risk to the bar casting team handling the moulds, pouring the molten and the PPE required to handle the very hot moulds. The thicker the PPE, the harder it became to physically handle the hot, heavy moulds – both empty and during the tipping process. It was also a challenge to heat the moulds to this temperature and heat the moulds evenly on the gas table.

A decision was made to swop out the smooth finish moulds with the sand-blasted finish moulds and find ways to control the mould temperatures in the ranges which produced the lowest number of bars with buttons and plug-like defects. The next parameter to be investigated was how the temperature of the moulds increased and could be controlled relative to the number of rounds poured in a shift.

An interesting pattern emerged in the investigation into the mould temperatures related to pouring. As identified in chart 5, rough finish moulds had a less than 5% reject rate at room temperature; however, the rough finish moulds were in the minority and a plan had to be formulated on how to manage the mould set where – for at least three to four months – the majority of the moulds would be moulds with a smooth finish. There was a three-to five-month lead time to get a full set of moulds with a sand-blasted finish from the foundry. The foundry agreed to sand-blast the

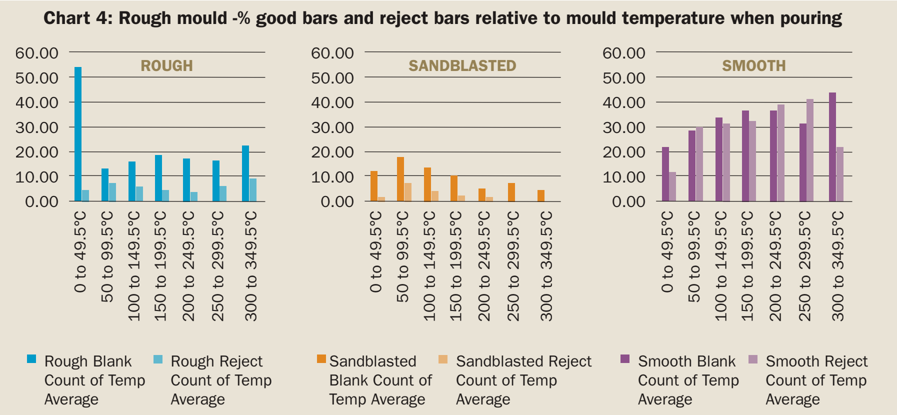

Chart 4: Rough mould -% good bars and reject bars relative to mould temperature when pouring

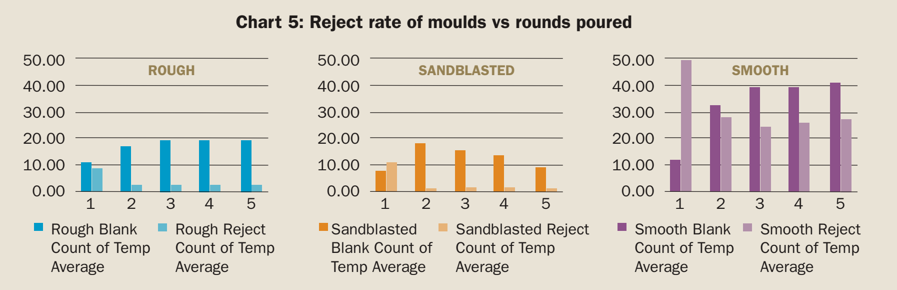
Chart 5: Reject rate of moulds vs rounds poured

smooth finish moulds that Rand Refinery had in stock and these were received over a period of three months.

In an attempt to get the lowest reject rate from the smooth finish moulds while waiting for the sand-blasted finish moulds to come on site, the mould set was heated up using the gas heating table. It can be seen that there was always a high reject rate in the first round. It was assumed that the mould heating table was heating the moulds unevenly. A decision was made whereby the first round poured would be used to heat the moulds up as this was the most efficient way to get the uniform heating required. The bars produced in the first round were always discarded and the bars produced from the second round onwards were counted and went through the normal process. It can be seen from the graphs in chart 5 that, with each successive round poured, the moulds became hotter and the reject rate stabilised. The number sand-blasted finish moulds tapered off on rounds four and five as the moulds would become too hot and were removed from the process. Rough finish moulds produced a consistently low reject rate with respect to button and plug formations regardless of the number of rounds poured in one shift.

Reject Rate Improvement

Based on the findings, it was obvious that the smooth finish moulds had to be removed from the process. Chart 6 indicates the change in the reject rates as the smooth finish moulds were removed from the process and the sand-blasted finish moulds were added in.

It should be noted that that a ‘blank’ bar is a bar free of buttons and/or plug-like defects and was considered to be a good bar.

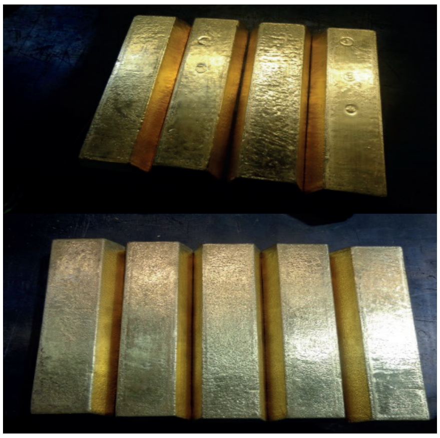
Figure 6

The photographs in figure 6 show the change in the surface finish on the underside of the bars from the smooth finish moulds (upper photo) and the sand-blasted finish mould (lower photo). It can be seen that the reject rates were still too high and the business had to make a decision to find a new solution.

Continuous Induction Furnace (CIF)

A solution had to be found to make a low-cost, repeatable, zero-defect London Good Delivery bar using a continuous induction furnace. The brief was to find a solution to produce 100 LGD bars in six hours from granule feedstock. The target reject rate of blank bars after production was less than 5%. Preferably, the surface treatment of the bar produced must be minimised.

A decision was made to go back to the technology used in the continuous induction furnace for the production of kilo cast bars and to see if there was a possibility of developing an in-house solution using this technology. In 1999 to 2002, Rand Refinery and IECO developed a CIF to produce kilo cast bars. A decommissioned kilo bar CIF was rebuilt on-site between April and September 2016. Testing work commenced and, by December 2016, the modified CIF was ready to go into production. On 2 December 2016, Rand Refinery stopped a 97-year process of hand-pouring LGD bars and moved over to production of LGD bars in a CIF.

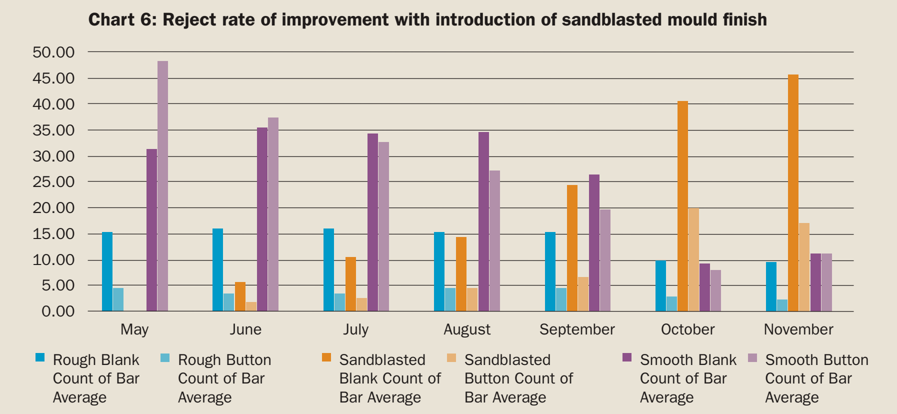
Chart 6: Reject rate of improvement with introduction of sandblasted mould finish

Operation

The cost to rebuild the furnace was less than €50,000, with cycle time of 170 seconds and an average reject rate of less than 3%.

The kW setting of the inverter is below 150 kW. The temperature of the mould after the furnace is at approximately 1,250°C when it passes from the furnace to the cooling zone.

Improvement on Surface Quality

The quality challenges no longer relate to button and plug-like defects. The new challenges primarily relate to the top surface blemishes which can be traced back to specific impurities in the feedstock used to produce the bars. An example would be iridium in the granules which affect the surface finish of the bar.

Conclusion

A solution to reduce the formation of buttons and plug-like defects at a cost-effective and in a timely fashion was not found. Since the LGD bar is produced at a zero profit to refineries, LGD bar production is avoided and production is completely dependent on market conditions. Investing €500,000 to find a technical solution was not feasible.

Rand Refinery is fortunate to have highly skilled and knowledgeable individuals. These individuals were able to find a solution involving a small investment which has changed the way this team operates, improving both the health and safety of the team and the quality of London Good Delivery bars produced.

Acknowledgements: Peter Bouwer, Chris Horsley and Willem Schoombee

Ilonka Macdougall joined Rand Refinery in late 2013. She is responsible for the production of cast bars, minted bars, coin blanks, product quality control, finished goods and despatch, mass metrology. She also manages the asset maintenance team dedicated to the fabrication Business Unit.

Prior to joining Rand Refinery she spent 20 years in the pharmaceutical industry. Her experience encompassed the areas of research and development, regulatory compliance, new business development, marketing, supply chain, project management and validation. She studied Analytical Chemistry at Technikon Witwatersrand (now the University of Johannesburg) and has a BCom degree in supply chain management and Total Quality Management from the University of South Africa.