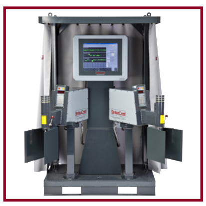
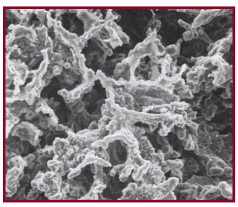
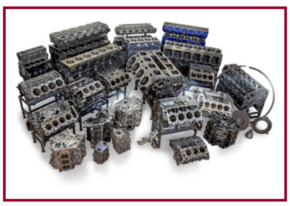
SinterCast

— Supermetal CGI —

A Novel Approach to Process Control and Traceability in the Cast Iron Foundry Industry

A Novel Approach to Process Control and Traceability in the Cast Iron Foundry Industry

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Introduction

Advanced materials and improved foundry technologies are needed to meet the increasingly stringent design, performance and durability requirements established by automotive OEMs. Increasingly, Compacted Graphite Iron (CGI) has become a material of choice for engine designers to satisfy performance objectives while reducing engine size and weight. In order to support the growing demand for CGI, foundries have adopted state-of-the-art process control technology to ensure reliable high volume series production, and to provide confidence to the OEM community. This paper provides an overview of the process control technology and traceability implemented by the Tupy Saltillo foundry for the high volume production of CGI cylinder blocks.

With the start of production of two petrol engine cylinder blocks in 2015, Tupy Saltillo established itself as the first high-volume producer of CGI cylinder blocks in North America, and as the world's first high volume producer of CGI cylinder blocks for petrol engines. Tupy Saltillo's parent company, Tupy S.A., has manufacturing facilities in Joinville in the State of Santa Catarina and in Mauá in the State of São Paulo, Brasil; and, in Saltillo and Ramos Arizpe in the State of Coahuila, Mexico. Tupy is one of the world's leading suppliers for the casting and machining of cast iron cylinder blocks and heads and is a recognised global CGI foundry organization with 18 CGI components in series production.

In preparation for the start of series production of petrol engine cylinder blocks, Tupy Saltillo installed the SinterCast System 3000 *Plus* process control technology, with the capacity to process up to 20 ladles per hour. Tupy Saltillo has also become the first foundry in the world to install the SinterCast Ladle Tracker™ technology, a novel radio frequency identification and tracking system that tracks and logs the time and location of every ladle at every step in the process including: furnace tapping; base treatment; correction; and, pouring. The Ladle Tracker™ technology links process data such as temperature, weight, chemistry and CGI thermal analysis results to each ladle to ensure that every step is completed correctly, and within the allocated time. The quantitative production records provided by the Ladle Tracker™ technology can identify bottlenecks and areas where ladles fall-out of the process, allowing foundry engineers and managers to optimise the foundry process flow and the overall production efficiency.

CGI Engine Design Opportunities

The use of CGI in diesel engines, both for passenger vehicle cylinder blocks and for commercial vehicle cylinder blocks and heads is well established. Since the start of series production of CGI cylinder blocks for passenger vehicle diesel engines in 1999, CGI has effectively become the standard material for V-diesel engines. Ford Motor Company, the global leader with nine engines using CGI cylinder blocks and/or heads, has adopted CGI for the cylinder block of its new 2.7 and 3.0 litre V6 petrol engines. The 2.7 litre engine is currently used in the Ford F-150, Focus and Edge, while the 3.0 litre version, with 400 horsepower, is available in the three Lincoln vehicles, including the new Lincoln Continental.

As shown in Figure 1, the graphite particles in Compacted Graphite Iron (sometimes referred to as vermicular cast iron) appear as individual 'worm-shaped' or vermicular particles. The compacted graphite particles are elongated and randomly oriented as in gray iron, providing good damping properties, castability and machinability. However, in contrast to gray iron, the compacted graphite particles are shorter and thicker and have rounded edges, providing higher strength, stiffness and fatigue resistance. While the compacted graphite particles may appear as individual vermicular particles when viewed on a two-dimensional plane of polish, deep-etched SEM micrographs (Figure 2) show that the compacted graphite particles are interconnected. This complex graphite morphology, together with the rounded edges and irregular bumpy surfaces, results in strong adhesion between the graphite and the iron matrix. Ultimately, the compacted graphite morphology inhibits both crack initiation and propagation and is the source of the improved mechanical properties relative to gray cast iron.

Figure 1: CGI microstructure

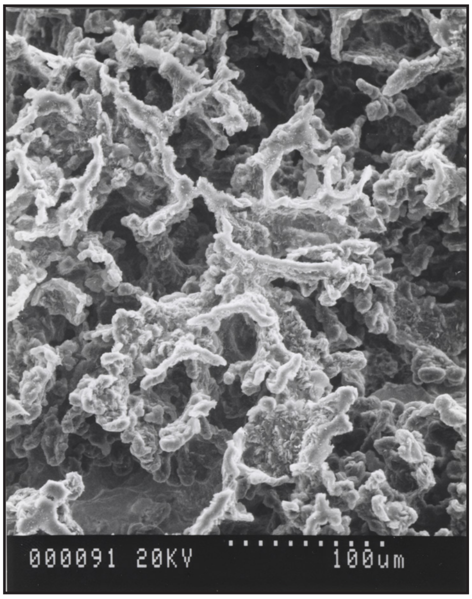

Figure 2: Deep-etch SEM photo of CGI microstructure

Compacted Graphite Iron provides at least 75% higher tensile strength, 45% higher elastic modulus and approximately double the fatigue strength of gray cast iron and the conventional aluminum alloys. These properties enable design engineers to reduce the thickness of load-bearing walls and thus to reduce the size and weight of the cylinder block. The improved properties of CGI also enable increased combustion temperature and pressure, to realise increased power and torque levels while ensuring durability in the downsized engine. In the present case, Ford realised the following design and performance benefits:

- 2.5 mm minimum wall thickness
- Minimal bore spacing to reduce the overall engine length
- Parent bore configuration; no cylinder liners or coatings
- Open deck design for thermal efficiency; enabled by CGI strength and stiffness
- 40 mm shorter than the aluminum design option
- Similar weight to the aluminum design option
- Improved crankcase ventilation due to open design structure
- Fracture split main bearings
- Up to 133 horsepower per litre

As shown in Figure 3, the unique design of the Ford V6 cylinder block incorporates fracture split main bearings extending below the main thermal mass of the cylinder banks, and an open deck configuration. This novel design approach initially presented dimensional stability control challenges due to residual stresses. These challenges were overcome by the foundry and, after more than one full year of series production, Tupy Saltillo has a proven track record for robust and consistent CGI production of one of the most complex cylinder blocks currently in production.

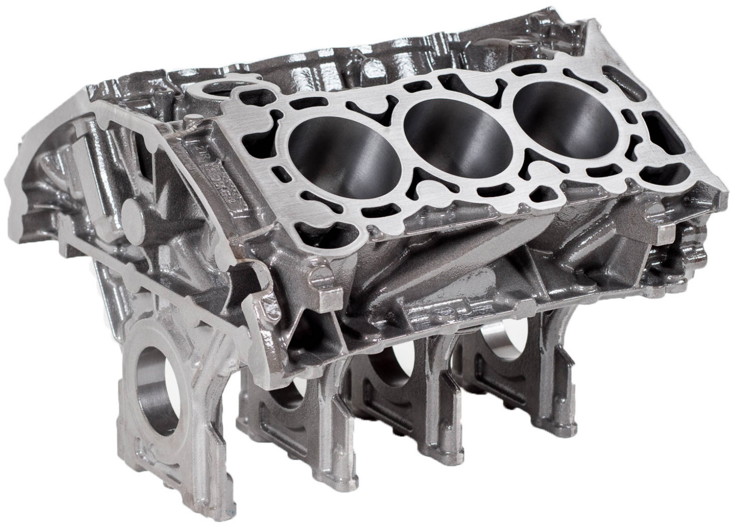

Figure 3: Ford's state-of-the-art 'Nano' V6 petrol engine is based on a CGI cylinder block with parent bore cylinders, fracture split main bearings, and 2.5 mm minimum wall thickness. The entire load path is comprised of CGI

CGI Process Control

The Ford specification for the 2.7 and 3.0 litre V6 CGI cylinder blocks required the graphite microstructure to be in the range of 0-20% nodularity and the matrix to contain >90% pearlite. The three-sigma minimum tensile strength requirement, measured in the cylinder block, was 420 MPa. The narrow 0-20% nodularity microstructure window was established to optimise the castability, machinability, thermal conductivity and vibration damping. However, the narrow nodularity range requires precise control of the magnesium content, typically within a range of +/- 0.003% Mg. Insufficient magnesium can rapidly lead to the onset of flake graphite, causing local weakness, or to the formation of an unacceptably thick flake graphite skin in contact with the core surfaces (specified maximum: 300 µm). At the same time, excessive magnesium and/or high inoculant levels can cause nodularity in excess of 20%, requiring increased feeding and increased risk of shrinkage defects in the foundry; adhesive wear in machining; and, potentially, galling in the cylinder bores during service. In order to reliably remain within the narrow specification range, Tupy Saltillo adopted the SinterCast process control technology. This technology has been successfully used at the Tupy foundries in Joinville and Mauá Brasil since 2003 for the production of several million cylinder block, cylinder head and bedplate castings according to the same microstructure specification, with as-cast weights ranging from 20 kg to 400 kg.

The SinterCast process control technology is based on a two-step measure-and-correct control strategy. The process begins by base treating the iron with magnesium, rare earths, and inoculant in cored wire form. After the base treatment, a 200 gram sample of the base-treated iron is obtained by immersing the SinterCast thermal analysis Sampling Cup (see Figure 4) into the liquid iron for approximately three seconds. While the sample solidifies, the ladle is deslagged and transported to one of two wirefeeder correction stations. When the analysis is completed, corrective additions of magnesium and inoculant cored wire are added, and the ladle is released for pouring. The magnesium fade clock begins at the conclusion of the correction treatment. During series production, the average addition of magnesium in the final correction step is approximately 30 grams/tonne (one ounce per ton), adjusting the fourth decimal point of the magnesium concentration. The measure-and-correct control strategy compensates for the variation that naturally occurs in the foundry and eliminates the risks associated with flake type graphite or porosity defects appearing in the final product.

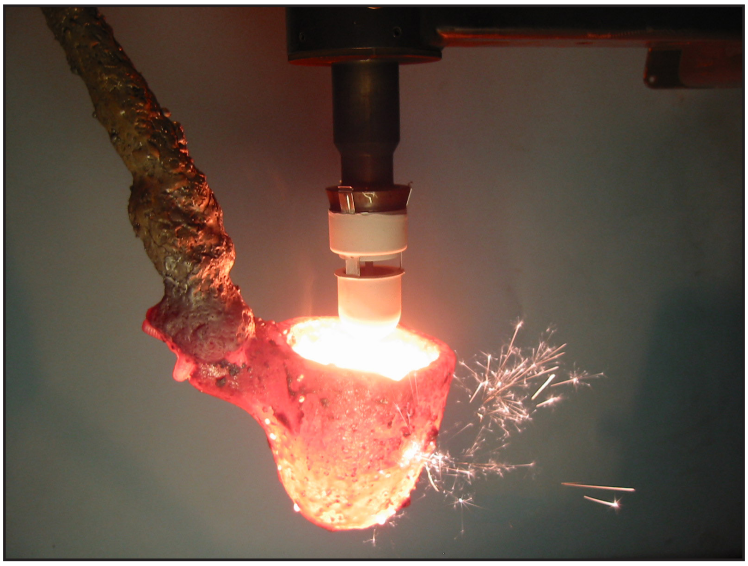

Figure 4: The SinterCast Sampling Cup provides more consistent sampling conditions and better resolution than conventional sand cups

In addition to the feedforward correction of each ladle prior to casting, the thermal analysis results from each base treatment are used in feedback control to improve the efficiency and consistency of the base treatment operation. The historical base treatment results are used together with automatically incorporated process data from the furnace scales and temperature devices to calculate the optimal base treatment alloy requirements for each new ladle. The Alloy Calculator function within the System 3000 *Plus* software continually adjusts the base treatment additions to achieve the pre-set targets for Modification (the combined treatment effect of magnesium and rare earth alloys, counteracted by oxidizing elements such as sulfur) and Inoculation.

The SinterCast System 3000 *Plus* installed on Line 3 at Tupy Saltillo has been specified and installed to process up to 20 ladles per hour, with the upper limit being established to coincide with the ladle movement capacity in the foundry. The system is modular and can be expanded in the future as the production volumes increase. The System 3000 *Plus* currently consists of four Sampling Modules (SAMs) to concurrently obtain the thermal analysis samples, one Automated Wirefeeder for base treatment of magnesium and inoculant, two Automated Wirefeeders for feedforward correction of magnesium and inoculant, one Operator Control Module (OCM) to display the process results and allow operator interaction with the system and, one Peripheral Input Module (PIM) to interface with ancillary equipment in the foundry and to automatically incorporate ladle weight and temperature information. The Sampling Modules and the Operator Control Module are shown in Figure 5.

Figure 5: SinterCast System 3000 Plus – SAMs and OCM

Ladle Tracker™ Technology

System 3000 *Plus* was further upgraded in 2015 with the first-ever installation of the SinterCast Ladle Tracker™ technology. The SinterCast Ladle Tracker™ technology monitors and records the progress of each ladle as it moves through the foundry. A robust Radio Frequency Identification (RFID) tag (Figure 6) is affixed to each ladle and RFID reader antennae (Figure 7) are installed at key locations throughout the foundry. In Tupy Saltillo, ladles are monitored at each of the three furnaces where iron for base treatment is tapped (two medium frequency induction melting furnaces and one channel induction holding furnace); at each of the wirefeeders used for base treatment and correction; and at each of the two pouring cars. Two antennae, synchronised to increase signal robustness, are used in many locations where distance within the coverage area or signal reflection off of metallic structures can interfere with ladle detection. Calibration of the antenna intensity and careful positioning is required to insure sufficient signal strength to energise the passive RFID tags, while avoiding crosstalk (simultaneous ladle detection in multiple locations). Where obstructions (wirefeeder enclosure doors) or ladle movement (pouring cars and forklifts) can interrupt the established connection between the ladle RFID tag and the antenna, a software locking mechanism has been specifically developed to hold the ladle in position until it is detected at exit. Locking a ladle in position insures that only one ladle can occupy a position and its status can remain positive (present and detected) despite the signal interruption. Antennae are connected to RFID Reader Boxes that interface with the System 3000 *Plus* through Ethernet connections. The separation distance allows multiple antennae to be connected to one Reader Box.

Figure 6: RFID tags affixed to ladles

Figure 7: RFID Antennae located at key positions in the foundry

In the production environment, a specifically designed solution was developed to protect the RFID ladle tags from heat, metal splash, impact and dust; while insuring that the tags were located in a readily readable location. Direct measurements found the surface temperature of the ladle peaked at 340°C while the tag must be kept below 120°C to preserve reading distance and usable life. A holder was developed to minimise the radiant heat from the ladle surface and from the convective heat rising from the base, keeping the peak temperature of the tag below specification. The reader antennae are also protected from heat and dust by a splash resistant refractory cloth and by placing the antennae in locations that enable reading while minimizing risk of physical and thermal damage. The design solutions have proven highly robust with no antennae failures in more than 25,000 ladle cycles and with RFID tag life exceeding one thousand cycles on many ladles.

The Ladle Tracker™ technology documents the time of the ladle at every position; ensures that every ladle reports to every step in the process; and ensures that each step is completed successfully within the allocated time. The main features and process opportunities of the Ladle Tracker™ technology include:

Process Security: Real-time process control to ensure that every ladle reports to every station and that time limits are adhered to, including automated lock-outs at the pouring cars.

Process Optimisation: Daily, weekly and/or monthly reports of ladle movement to identify where and why ladles drop-out of the process and to identify and resolve process bottlenecks.

Process Improvement: Establish production KPIs to link operator performance directly to productivity and to quantitatively measure process improvements.

Process Traceability: Ladle movement and process data (temperatures, weights, chemistries, thermal analysis results, and wirefeeder data) can be uploaded to the foundry database for process traceability and customer assurance. No process information is stored on the RFID Tag.

Remote Office Display: Foundry supervisors and managers can view real-time process data on remote computers via internal network connections.

CGI Process Flow with Ladle Tracker™

Melting of low-sulfur base iron is performed in two, 12 tonne medium frequency induction furnaces. Ladles are tapped directly from these melting furnaces or from a 30 tonne holding furnace that is filled by the melting furnaces during non-CGI production periods. Up to five ladles are rotated through the CGI process to maintain a steady supply of iron to the molding line. The ladle capacity varies between 1350-1750 kg, providing a maximum CGI pouring capacity of 35 tonnes/hour. Ladles positioned at any furnace for tapping are detected and identified by Ladle Tracker™ as shown in Figure 8. A signal lamp provides operators with a confirmation that the RFID tag has been detected. When the iron has been tapped, the furnace operator registers the melt by pressing the registration button. Upon registration, the tapped weight and ladle ID are automatically input to System 3000 *Plus*.

Figure 8: Ladle Tracker™ at tapping furnace

Ladles are transported to base treatment by forklift, where the iron temperature is measured and automatically input to System 3000 *Plus*. The Ladle Tracker™ identifies the ladle placed in the base treatment wirefeeder enclosure (the center enclosure in Figure 9), and insures all process inputs are appropriately applied. The System 3000 *Plus* Alloy Calculator function utilises the SinterCast thermal analysis results of the previous ladle, together with the automatic inputs of iron weight, temperature and base iron sulfur content of the current ladle to calculate the optimal base treatment additions of magnesium, rare earths and inoculant. All input parameters registered to that melt ID must be within preset limits for the System 3000 *Plus* to execute the base treatment. Non-conforming ladles are flagged early in the process.

Figure 9: System 3000 Plus – base treatment (center) and correction enclosures (north and south)

System 3000 *Plus* signals the operators to remove the successfully base treated ladles for thermal analysis sampling and transfer to either of the two available correction enclosures. The Ladle Tracker™ automatically determines into which correction wirefeeder the ladle has been placed, preventing any potential error in assigning corrective wire additions to a ladle. When the SinterCast thermal analysis results are complete, the correction wire lengths are sent only to the wirefeeder enclosure that contains the ladle with the matching RFID tag.

Ladles leaving correction are transported by forklift to one of two pouring cars. When a ladle enters the pouring car, Ladle Tracker™ identifies the RFID tag and provides a green signal lamp to indicate the ladle is approved for pouring (all process steps successfully completed, all input values and permissible pouring time within range), as shown in Figure 10. If all parameters are not within the specifications set by the foundry engineers, the red signal lamp will be illuminated and the ladle will be locked-out to prevent pouring. The time elapsed from completion of the correction step is recorded by Ladle Tracker™. When the time limit for pouring is about to expire, a warning indication is provided to the pouring car operator. This warning allows the operator to finish pouring the current mold. Thereafter, the red signal lamp illuminates and pouring is automatically locked-out (molds cannot be poured). The automatic lock-out insures that the foundry does not have to rely on operator discipline, thus providing control for the foundry and confidence for the OEM.

Figure 10: Ladle Tracker™ at semi-automatic pouring line

Ladle Tracker™ Feedback

A Ladle Tracker™ status window has been integrated into the System 3000 *Plus* OCM feedback screen. The status window lists each Ladle Tracker position and indicates the presence of a ladle by the affixed RFID tag. Color coding defines the status of each ladle, with green indicating that the ladle has been registered and accepted at that position, yellow signifying that the ladle has been registered but is waiting for completion of a sample or other data and red meaning that the ladle has been rejected, either for an out-of-range value, incorrect positioning or for exceeding the time limit. The OCM feedback screen, including the Ladle Tracker™ status window, can be viewed remotely on any foundry computer on an attached network using the SinterCast OCM-Viewer software. The OCM-Viewer allows managers and supervisors to view current results in real time and to scroll back through past results from any convenient foundry network location, such as offices and meeting rooms.

The SinterCast Customer Access Terminal (CAT) provides an engineering interface between System 3000 *Plus*, including Ladle Tracker™, and the Tupy Saltillo engineers. Tupy Saltillo engineers can connect to the System 3000 *Plus* from any foundry network location to manage and set the production parameters of each CGI casting and to download results and summary reports. System 3000 *Plus* summary reports can be created on a daily, weekly, monthly or on-demand basis. The Ladle Tracker™ report is customised for the foundry to detail the timing of ladles passing through the process. The report data can also be exported in a text stream, in real time, to a foundry controlled database.

Reports of the average start time at each measurement position, and elapsed times for each step in the process, allows the production performance to be measured and bottlenecks to be identified and resolved. The timing data are organised by furnace, correction and pouring locations to accurately identify when and where ladles drop out of the process. Ancillary data such as ladle weight, temperature and sulfur can be used to further identify the reasons why ladles may drop out of the process, creating a powerful tool for productivity improvement. RFID tag life statistics are included in the summary reports to assist with maintenance. Log reports, also downloaded with the CAT software, detail maintenance alerts or errors related to the Ladle Tracker™ hardware. The comprehensive communication interface between System 3000 *Plus*, Ladle Tracker™ and foundry process inputs insures that operational security is achieved and system benefits are maximised.

Summary

Building on more than ten years of high volume Compacted Graphite Iron series production at the Tupy foundries in Brasil, Tupy and SinterCast designed and installed a bespoke CGI process at the Tupy Saltillo foundry in Mexico prior to the start of production of the world’s first high volume CGI petrol engine cylinder block for Ford Motor Company. The unique design of the cylinder block, with fracture split main bearings extending below the thermal center of the block, and with 2.5 mm minimum wall thickness, presented significant technical challenges for the foundry, which have all been successfully overcome. The high throughput, with capacity to process up to 20 ladles per hour, using multiple furnaces, multiple treatment stations and multiple pouring cars, also required the development of a novel ladle tracking solution to ensure that every ladle completes every step in the process flow, within the boundaries set by the foundry engineers. The Ladle Tracker™ technology has provided a new level of process security for the operators and a new level of insight for the foundry managers, both for continuous improvement of the process and for traceability of the product.

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