

Effect of Carbon Equivalent and Graphitization Potential on Eutectic Expansion in Gray Cast Iron

Sarum Boonmee

sarum@sut.ac.th

Suranaree University of Technology

Auttachai Utsajai

Suranaree University of Technology

Research Article

Keywords: gray cast iron, eutectic expansion, solidification shrinkage, graphitization potential, carbon equivalent, inoculation, thermal analysis, linear displacement analysis

Posted Date: September 8th, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-10851698/v1>

License:   This work is licensed under a Creative Commons Attribution 4.0 International License.

[Read Full License](#)

Additional Declarations: No competing interests reported.

EFFECT OF CARBON EQUIVALENT AND GRAPHITIZATION POTENTIAL ON EUTECTIC EXPANSION IN GRAY CAST IRON

S. Boonmee* and A. Utsajai

Suranaree University of Technology, Nakhon Ratchasima, Thailand

*sarum@sut.ac.th, ORCID = 0000-0002-1789-1300

Copyright 2026 American Foundry Society

Abstract

Eutectic expansion resulting from graphite formation is a key factor in compensating for solidification shrinkage in cast irons. However, quantitative measurement of this expansion remains challenging because of some difficulties such as mold-wall movement and the complex dimensional response of the metal during solidification. In this study, a combined Thermal Analysis and Linear Displacement Analysis (TA-LDA) approach was developed to investigate the effects of silicon, carbon equivalent (*CE*), graphitization potential (*G.P.*) and inoculation on eutectic expansion. A spherical casting geometry produced using 3D-printed resin sand molds and encased in a rigid steel case was employed to minimize directional and mold-wall effects. Increasing Si and *G.P.* promoted stable eutectic solidification, suppressed carbide formation and increased both total expansion displacement and expansion time during eutectic solidification. Increasing *CE* similarly increased the expansion due to the greater amount of eutectic graphite formed. The condition with a hypereutectic composition exhibited the greatest expansion. Correlation analysis showed strong positive relationships of total expansion displacement with Si ($r = 0.90$) and *CE* ($r = 0.88$), while shrinkage displacement was strongly negatively correlated with Si ($r = -0.98$). Increasing inoculation also increased the total expansion displacement and expansion time despite nearly constant *CE*, showing the importance of graphite nucleation in controlling expansion behavior. The results show that eutectic expansion in gray iron is governed by the combined effects of carbon equivalents, graphitization potentials and inoculation. The developed TA-LDA method provides a practical approach for quantifying solidification expansion.

Keywords: gray cast iron, eutectic expansion, solidification shrinkage, graphitization potential, carbon equivalent, inoculation, thermal analysis, linear displacement analysis

Introduction

Gray cast iron (also known as lamellar graphite iron, LGI) is the most used cast material in engineering applications like engine blocks, brake rotors and machinery parts. Its castability, thermal conductivity and damping capability make it an ideal candidate for these applications. Gray iron demonstrates eutectic expansion which is the volumetric increase resulting from graphite formation during eutectic solidification. Unlike most metals which shrink upon solidification, gray iron exhibits little to no net shrinkage or overall expansion. This is due to the lower density of graphite relative to liquid iron and austenite [1]. This behavior has practical implications for casting design: in many cases gray iron castings can be made riserless because graphite expansion compensates for the

solidification shrinkage [2]. However, controlling eutectic expansion is critical as excessive expansion mold wall movement causing microshrinkage or scabs due to failure of green sand molds [1].

Typical compositions in industrial practices range from hypoeutectic to eutectic compositions. The solidification of gray iron is associated with the formation of primary austenite (for hypoeutectic composition) or primary graphite (for hypereutectic composition) and the eutectic mixture of austenite and graphite. Graphite has a significantly lower density ($\sim 2.1\text{--}2.2\text{ g/cm}^3$) compared to liquid iron or austenite ($\sim 7.0\text{--}7.3\text{ g/cm}^3$ for austenite). Consequently, when the formation of graphite occurs during the eutectic solidification, the volumetric expansion occurs. In fact, the eutectic expansion can offset the shrinkage from primary austenite for near-eutectic composition under equilibrium conditions. However, equilibrium conditions rarely occurred in industrial practices. The actual volume change depends on solidification kinetics, the fraction of primary phase, and graphite nucleation and growth dynamics.

In hypoeutectic gray irons, solidification begins with primary austenite dendrites formation. Austenite is denser than liquid iron causing an initial contraction. As solidification reaches the eutectic temperature, the eutectic mixture starts to grow (the coupled growth between graphite and austenite) and partially counteracts the shrinkage. The net volume change during solidification is the result of this competition between austenite shrinkage and graphite expansion. Tadesse and Fredriksson [3] observed that a casting with carbon equivalent near eutectic showed “hardly any shrinkage during early solidification” and then expanded continuously during the eutectic reaction until the end of solidification. On the other hand, the solidification of hypereutectic gray iron is associated with the formation of primary graphite which creates additional expansion followed by eutectic reaction. Therefore, the net volume expansion of the hypereutectic gray iron is higher than the hypoeutectic and eutectic gray irons.

Another factor that contributes to the volume change during solidification of gray iron is the cooling rate. It is known that higher cooling rate favors the metastable solidification resulting in carbide formation. When carbide formation occurs, volume fraction of graphite is lower and less expansion during eutectic reaction available to compensate for the shrinkage, increasing the risk of microshrinkage formation. Furthermore, Alonso et al. [4] reported that slow cooling rate led to higher expansion in gray iron castings. Faster cooling rates typically result in a higher fraction of austenite than the equilibrium; hence, lower the degree of eutectic expansion. Adding carbide forming elements (such as Cr and Mo) to gray iron also reduces the eutectic expansion. This effect has been demonstrated by Stuewe et.al [5].

There have been researches on understanding and modeling eutectic expansion in gray iron. These studies date back to as early as 1954 by Schmidt et al. [6]. Table 1 summarizes the earlier studies by various investigators. In-depth discussions and details can be found in the study by Svidró et al. [7]. Overall, the technique used can be categorized into two groups; (i) using a buoy made from refractory materials to keep track of volume change during solidification; (ii) using linear displacement measurements with instruments such

as LVDT (Linear Variable Displacement Transformer) or dilatometer attached to probes that contact the solidifying metal. Nevertheless, modern research on eutectic expansion has predominantly employed LVDTs. The general setup involves a test casting (often cylindrical or bar-shaped) poured in a sand mold, with one or more quartz rods inserted to the top or side of the casting. As the casting expands or contracts, it pushes the rod and the movement is recorded by the LVDT transducer. A thermocouple is usually embedded to record the temperature change simultaneously. The advantage of this method is the ability to obtain a continuous expansion/contraction curve over time, which can be directly correlated with solidification events (e.g. eutectic undercooling, eutectic recalescence, end of solidification, etc.) on the cooling curve. This approach (TA-LDA: Thermal Analysis and Linear Displacement Analysis) was used by investigators [4, 15, 16] to discuss solidification events and feeding behavior in cast iron. There are challenges and difficulties in measuring the liquid contraction and expansion. One issue is distinguishing true metal expansion from mold or thermal expansion effects. If the mold wall moves or thermally expands, the errors are introduced in the measurements. Researchers addressed this by using low-expansion materials for probes (quartz is the most common due to its low thermal expansion and refractoriness) and by physically isolating the transducers from the mold movements (e.g. mounting LVDTs on a separate frame isolated to the mold). In addition, encasing the sand mold by materials with higher stiffness such as steel cases is an attempt to minimize the mold wall movement. An important challenge of using LVDT approach is the detection of the early liquid contraction. This is due to the incoherency of the solidifying metal with the tip of quartz rods resulting in inconsistency results in the early stage of solidification. Another difficulty is the loss of pressure through parting line of the molds which introduces negative errors to the expansion measurements. Finally, mold geometry can introduce anisotropy of expansion (e.g. expansion depends on orientation of the measurement). Svidró and Diószegi [7] employed the multiaxial measurements demonstrated that in a horizontally cast cylinder, the axial expansion can differ from the radial expansion. They reported that the metal can contract in one direction while expanding in another. Overall, the measurement of liquid contraction and eutectic expansion is very challenging. The results can be complicated despite the careful design of the experiment. Finally, the linear displacement can be used to predict the volumetric changes by converting the linear strain ($\Delta L/L$) into a volumetric strain ($\Delta V/V \approx 3\Delta L/L$) assuming the uniform isotropic expansion in a rigid mold. Consequently, data on linear displacement measurements are valuable for the modeling of casting processes and the development of simulation software.

Table 1 Summary of previous studies on solidification shrinkage in cast iron

	Techniques	Casting geometry	Note
Schmidt <i>et al.</i> [6] (1954)	Graphite buoy Dial gauges in mold wall	Conical cylinder; vertical	Green sand mold
Zou <i>et al.</i> [8] (2012)	Graphite buoy LVDT on quartz rod	80 mm diameter Spherical	Bottom fed; encased in steel flask; vertical parting line
Stefanescu <i>et al.</i> [9] (1979)	LVDT on quartz rod Thermocouple	Thermal analysis cup	Furan mold (hot box)
Degois (1975) [10]	Displacement on silica rod	23 mm diameter; 175 mm long Cylindrical; horizontal	-
Hummer (1985) [11]	2 LVDTs on quartz rods Thermocouple	-	CO ₂ sand mold

Gedeonova <i>et al.</i> [12] (1995)	LVDT on quartz rod 2 Thermocouples (wall, center) Load cell on quartz rod	Cylindrical; vertical	-
Mrvar <i>et al.</i> [13] (2002)	LVDT on quartz rod Thermocouple	Thermal analysis cup	CO ₂ sand mold
Chisamera <i>et al.</i> [14] (2011)	LVDT on quartz rod Thermocouple	30 × 30 × 200 mm Square bar; horizontal	Green sand mold. Furan sand mold; both encased in a container
Stefanescu <i>et al.</i> [15] (2012)	LVDT on quartz rod (radial) Thermocouple	3" diameter; 3" tall. Cylindrical; vertical	Sodium silicate sand mold; vertical parting line
Svidró, Diószegi [7] (2013)	2 LVDTs on quartz rods (axial and radial) 2 Thermocouples (wall, center) Load cell on quartz rod	50 mm diameter; 350 mm long Cylindrical; horizontal	LVDTs mounted on a separated frame; Shell sand mold; horizontal parting line
G. Alonso <i>et al.</i> [4] (2014)	2 Thermocouples, 2 LVDTs (top, bottom)	150 × 140 × 55 mm; Resin sand molds; Steel frame	Walls in front of the LVDT to prevent disturbance

The analytical model for predicting volumetric change of cast iron during solidification is typically based on the changes in density of associated phases (e.g. liquid, austenite, graphite). The most straightforward approach is using the rule of mixtures in which density is calculated by the fraction of phases. Lacaze *et al.* [17] developed models for density change during solidification of cast irons. They showed that density of liquid iron depends on carbon, silicon and temperature. Density of austenite was calculated based on lattice parameter in which carbon expands lattice and silicon contracts lattice. In addition, the formation of microshrinkage in ductile iron contributes to the larger expansion rate than gray iron.

As mentioned, there are many parameters that involve solidification contraction and expansion of cast irons. Among the most important parameters are the graphitization potential and carbon equivalents, given that both are the control parameters in the cast iron production. In addition, the effect of inoculation is related to the former parameters and commonly performed by the industries. Therefore, this study explores the effects of carbon equivalent, graphitization potential and inoculation in eutectic expansion in gray iron using the new displacement approach that overcome difficulties in measurement.

Experimental Procedure

Design of apparatus

A set of apparatus was specifically developed for TA-LDA analysis in this study. The design criteria are followings.

- The apparatus must allow the concurrent measurement of temperature and linear displacement as a function of time (e.g. cooling and displacement curve).
- The apparatus must provide mold rigidity to suppress the mold-wall movement which can obscure the measurement.
- The sand mold must have good repeatability to avoid variation between tests.
- The shape of casting should provide uninform (isotropic) expansion to avoid the effect of orientation and measuring location.

Figure 1 shows the TA-LDA apparatus used in this study. As seen, the casting shape was spherical with a diameter of 72.20 mm. The spherical shape is an ideal shape to provide the isotropic expansion during solidification. The molds were also in near-spherical shape with a thickness of 13.10 mm. The molds were made with resin sand (phenolic) manufactured by a 3D mold printing machine. A socket for thermocouple and a hole for quartz rod were integrated in the sand molds allowing easy and consistent installation between tests. The sand mold was encased in a steel case with a thickness of 13.30 mm providing minimal mold-wall movement. The thermocouple used was Type-S and connected to the data acquisition system to retrieve the cooling curve. The quartz rod was attached to an LVDT and then the data acquisition system to retrieve the displacement curve (with a data sampling rate of 2 Hz). Note that the bases for the casting and the LVDT were separated to avoid the expansion of the frame or bases. During the installation, the thermocouple and LVDT were tested and carefully placed and set zero where the quartz rod protruded 15 mm into the mold cavity. Note that the length of the protruding quartz rod was the same as the tip of the thermocouple. This was intentional to record the solidification event concurrently. During the test, the molten iron was poured into the hole at the top, then closed with the lid and weight to counteract the buoyancy force.

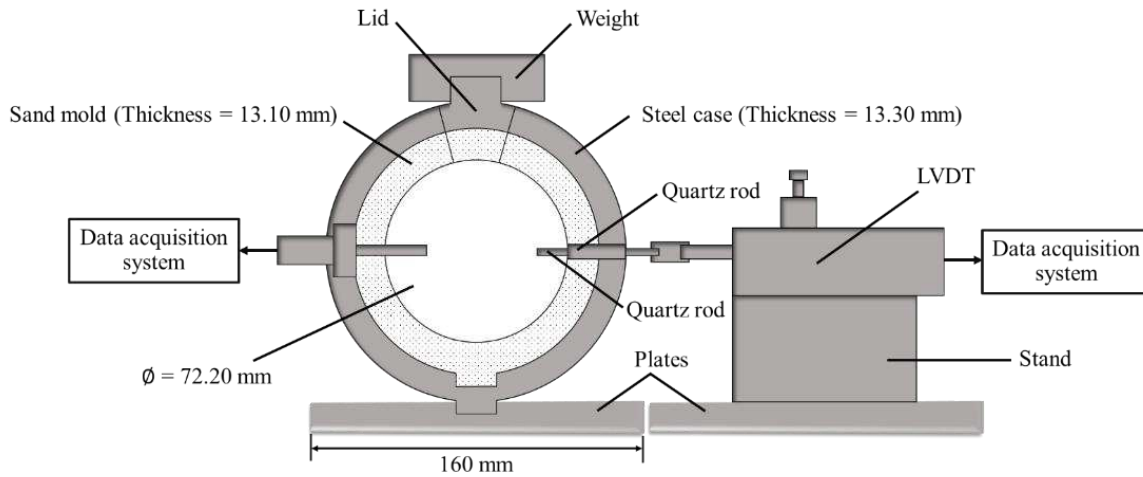


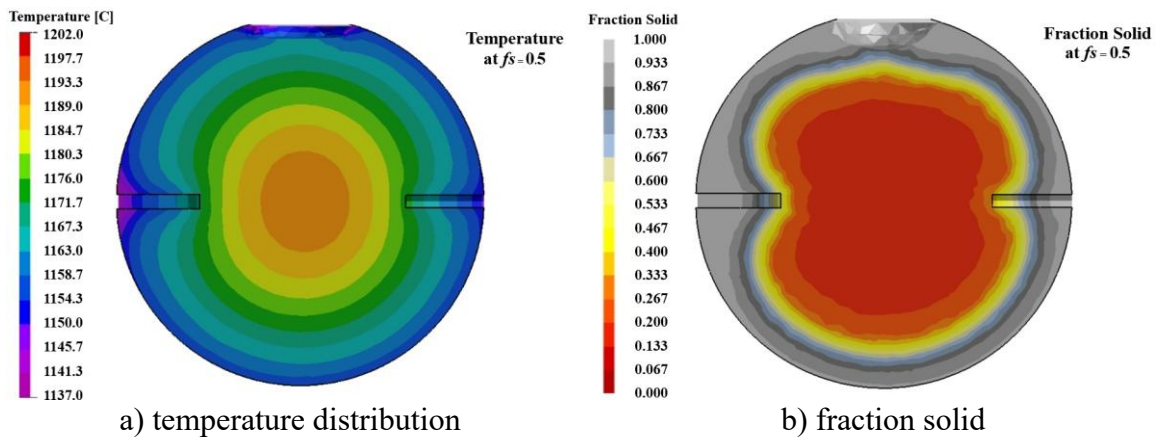
Figure 1 Details of TA-LDA apparatus in this study.

Figure 2 shows the TA-LDA apparatus setup. As seen, the spherical steel cases with the encased sand mold. The spherical steel cases are separated into two halves which are secured together by bolts when assembled. The thermocouple is to the right of the picture and the LVDT is on the other side fixed with a clamp to ensure the firm seating on the stand. Both bases (made from steel) are separated with a gap to avoid the thermal expansion of the bases themselves. It should be noted that the alignment of the quartz rod through the steel cases and a hole in the sand mold is very important and needs to be carefully adjusted before every experiment.



Figure 2 The TA-LDA apparatus; a) the setup (without the lid); b) the additive manufactured sand mold showing the seamless design and the socket for the thermocouple setting.

Casting simulations were conducted for the design. The objective of the simulations is to confirm that (i) the temperature distribution is symmetry between the thermocouple and the quartz rod sides; (ii) the solidification at the tip of the thermocouple and the quartz rod occur at relatively the same event; (iii) there is no void in the area of measurement. The simulation was conducted with a commercial casting simulation software. The cast material was gray iron Class 20 as per ASTM A48. The pouring temperature was 1380 °C. Figure 3 shows the simulation results. As seen, the temperature distribution shows symmetry for both sides of the casting. The temperature scale in the figure is set to range from the liquidus to solidus temperature. There is small chilling effect of the thermocouple and the quartz rod but the effect was insignificant. In addition, the fraction solid demonstrates that the solidification at the tip of the thermocouple and the quartz rod occurs relatively at the same time. Hot spot is also at the middle of the casting showing the good symmetric result. Finally, there is no void is predicted in the associated area (near the measuring and microscopic examination areas). All the voids is at the top of the casting due to solidification shrinkage.



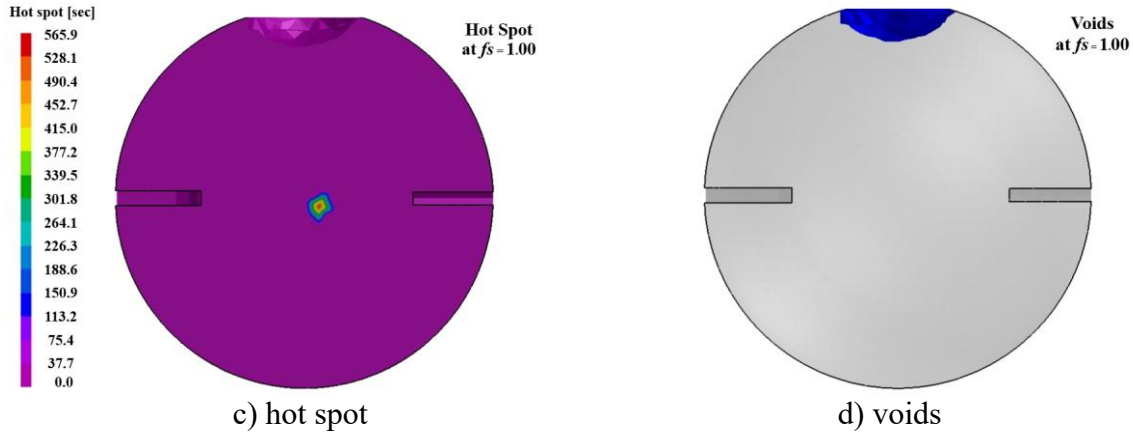


Figure 3 Simulation results; a) temperature distribution; b) fraction solid; c) hot spot; d) voids.

Liquid iron preparation

Eleven heats of gray irons were produced using a 100-kg induction furnace. The charge materials included pig iron, steel scrap, ferrosilicon (Fe–76.5% Si), ferromanganese (Fe–73% Mn) and a carbon raiser. The tapping and pouring temperatures were approximately 1450 °C and 1380 °C, respectively. Molten metal was transferred into a 30-kg capacity ladle for pouring. For some heats, inoculation was performed in the pouring ladle using a Sr-bearing inoculant (Fe-78Si-1.0Sr-0.1Ca-0.5Al). The molds were manufactured with 3D sand mold printing (phenolic as a binder). The first series of experiment consist with 7 heats with a range of silicon (0.02–2.06 %Si). This range was set up to observe the effects of graphitization potential (*G.P.*) using Si as the main factor. The heats with low Si were expected to exhibit carbide formation resulting in the limited eutectic expansion. As Si increased, a greater amount of expansion is expected. The second series of experiments consist of 4 heats with varying inoculation level ranging from 0 – 0.3% of the melt weight. An Optical Emission Spectrometer (OES) was used to determine the chemical composition of sampled gray irons.

Characterization

The microstructure of both unetched and 3% Nital-etched samples was examined using an optical microscope (OM). Samples were cut from the central region of the test castings. Image analysis software was used to quantify the percentage area of different phases. For graphite evaluation, unetched micrographs captured at 100× magnification were binarized using a defined threshold value. The resulting binary images were analyzed to calculate the percentage area of graphite. Any particles with an area smaller than 4 mm² were excluded from the analysis, as they were presumed to be polishing artifacts. To determine the percentage area of ferrite and pearlite, etched micrographs at the same magnification were analyzed. The percentage area of pearlite was calculated by subtracting the ferrite fraction from the total, assuming the combined percentage area of all phases equals 100. Data points were averages of 10 fields of measurements along with their standard deviations (error bars).

Density measurement

The Archimedes method was used to determine the density of the castings. The method is based on the principle of buoyancy as a body submerged in a fluid experience an upward buoyant force equal to the weight of the fluid it displaces. The castings were weighed in the air (W_{air}) and in the water (W_{water}). While weighing in water, the castings were completely submerged and hung by a wire with a weight (W_{wire}). The density of the casting was calculated by Eq. 1.

$$\rho = \frac{W_{air} \rho_w}{W_{air} - (W_{water} - W_{wire})} \quad \text{Eq. 1}$$

where W_{air} is weight of casting in air (kg)

W_{water} is weight of casting in water (kg)

W_{wire} is the weight of wire (kg)

ρ_w is density of water (kg / m³) depending on temperature (T in degree Celsius) calculated by Eq. 2 as per the MPIF standard 42.

$$\rho_w = 1.0017 - 90.0002315T \quad \text{Eq. 2}$$

Results and Discussions

Chemistry

Table 2 shows the chemical composition (in weight percent, %) of seven gray iron heats with varying Si, along with their carbon equivalent (CE) and graphite precipitation ($G.P.$). It is seen that Si increased from 0.02 – 2.06% which increased the graphitization potential and carbon equivalent. Carbon equivalent was calculated by Eq. 3

$$CE = \%C + (\%Si + \%P)/3 \quad \text{Eq. 3}$$

Carbon was kept relatively constant at 3.65 – 3.72% except Heat 7 with very high carbon (4.98%, $CE = 5.59$). The condition was set to observe the expansion behavior of very high CE (hypereutectic condition). Mn was kept at around 0.30 – 0.33% which is a common level in the industrial practice ($\%Mn = 1.7 \times \%Si + 0.3$). Phosphorus (P) was in the range of 0.027 – 0.032% which is a common range for gray iron production. Sulfur (S) was kept in the 0.03 – 0.06 range which is optimal for the subsequent inoculation in gray iron [18].

Graphitization potential ($G.P.$) was calculated using the role of alloying element in changing metastable and stable eutectic temperatures by wt% (ϕ' and ϕ) shown in Table 3. In this study, the levels of Cu, Cr, Ni and Al were in the range of 0.002 – 0.008%, 0.005 – 0.010%, 0.001 – 0.003% and 0.002 – 0.005% respectively which have negligible effect in $G.P.$ values. Therefore, the stable and metastable eutectic temperature (T_{st} and T_{meta}) were calculated by Eq. 4 and Eq. 5 respectively where 1154 and 1148 °C are the T_{st} and T_{meta} for unalloyed gray iron. The $G.P.$ was the difference between the two temperatures in the unit of °C.

$$T_{st} = 1154 (^{\circ}\text{C}) + \%Si \times \phi_{Si} + \%Mn \times \phi_{Mn} + \%P \times \phi_P \quad \text{Eq. 4}$$

$$T_{meta} = 1148 (^{\circ}\text{C}) + \%Si \times \phi'_{Si} + \%Mn \times \phi'_{Mn} + \%P \times \phi'_P \quad \text{Eq. 5}$$

Table 2 Chemical composition of gray iron in Series 1 (effect of Si, CE and G.P.).

Heat	Chemical composition (wt%)					CE	G.P. ($^{\circ}\text{C}$)
	C	Si	Mn	P	S		
1	3.72	0.02	0.31	0.027	0.04	3.74	6.93
2	3.70	0.48	0.32	0.029	0.04	3.87	16.03
3	3.70	0.95	0.30	0.032	0.03	4.03	23.45
4	3.72	1.49	0.32	0.032	0.05	4.23	34.31
5	3.65	1.80	0.31	0.032	0.06	4.26	41.48
6	3.67	2.06	0.33	0.035	0.03	4.37	45.73
7	4.98	1.78	0.35	0.033	0.05	5.59	42.69

Table 3 Influence of alloying element in changing in metastable and stable eutectic temperatures in cast iron. [19]

Alloying Element	Change in eutectic temperature ($^{\circ}\text{C}/\text{wt}\%$)	
	Metastable (ϕ')	Stable (ϕ)
Si	-20	+4
Cu	-2.3	+5
Al	-15	+8
Ni	-6	+4
Cr	+7	-
Mn	+3	-2
P	-37	-30

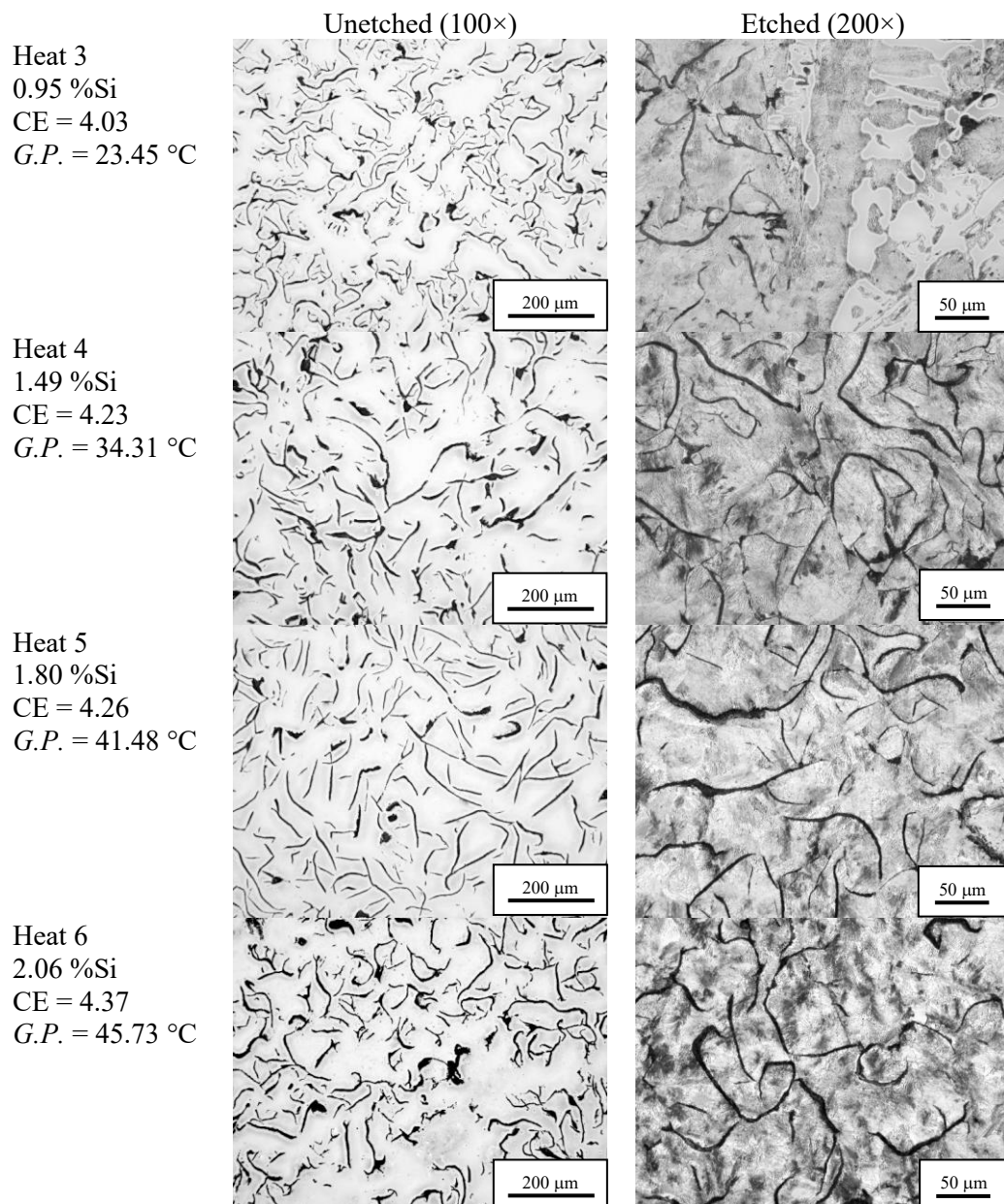
Table 4 shows the chemical composition of the gray iron in Series 2. The goal of this series is to observe the effects of inoculation on the eutectic expansion of gray iron. The inoculation levels were determined by the percent weight of inoculant by the melt weight from 0 – 0.3%. As seen, the variations in C, Si, Mn, P and S between heats were kept minimal to isolate the effect of inoculation from chemistry. Noted that the Si shown in the table is the Si after inoculation.

Table 4 Chemical composition of the gray iron in Series 2 (effect of inoculation level).

Heat	Condition	Chemical composition (wt%)					
		C	Si	Mn	P	S	CE
8	0 %Innoc.	3.66	2.07	0.38	0.029	0.05	4.36
9	0.1 %Innoc.	3.71	2.01	0.38	0.031	0.05	4.39
10	0.2 %Innoc.	3.71	1.92	0.38	0.031	0.05	4.36
11	0.3 %Innoc.	3.68	1.99	0.38	0.031	0.05	4.35

Microstructure

Figure 4 shows the microstructure of gray iron with varying graphitization potentials. It is seen that all conditions show Type-A graphite except Heat 7 which demonstrates Type-C graphite. This was due to very high C and Si (CE = 5.59) in Heat 7. As a result, primary graphite form before the eutectic reaction. The etched microstructure revealed the matrix. The dominant phase in the matrix was pearlite along with ledeburite. Amount of carbide was initially higher at low *G.P.* When *G.P.* increased, the amount of carbide decreased. In addition, graphite also increased with increasing *G.P.* Heat 7 has the highest graphite percentage due to its higher CE. Carbide formation was only found in Heat 1, 2 and 3. There was no carbide found for the samples with *G.P.* above 34.31 (Heat 5 - 7). Figure 5 shows the percentage of phases measured by the image analysis. The results support the findings described.



Heat 7
1.78 %Si
CE = 5.59
G.P. = 42.69 °C

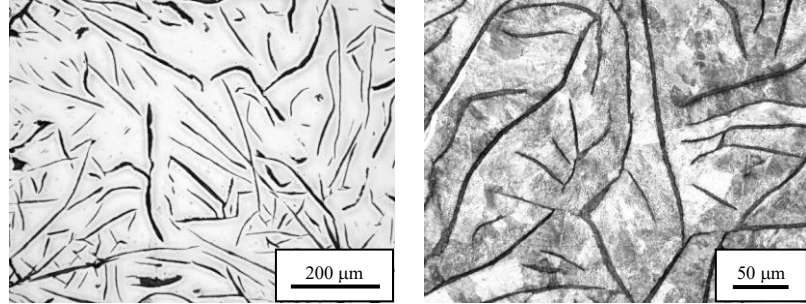


Figure 4 Selected OM micrographs of selected conditions of gray iron with varying graphitization potential (unetched, 100× and etched 200×).

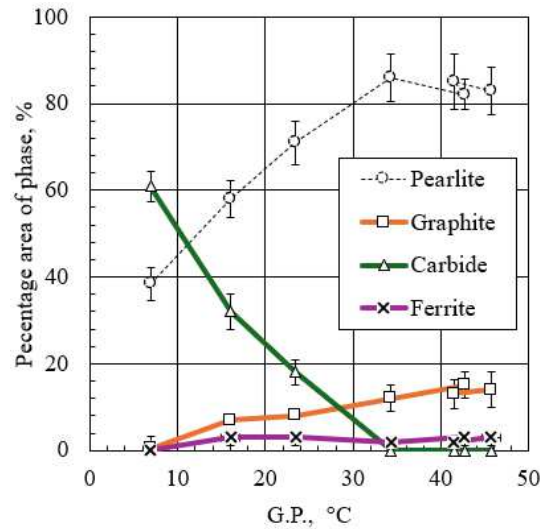
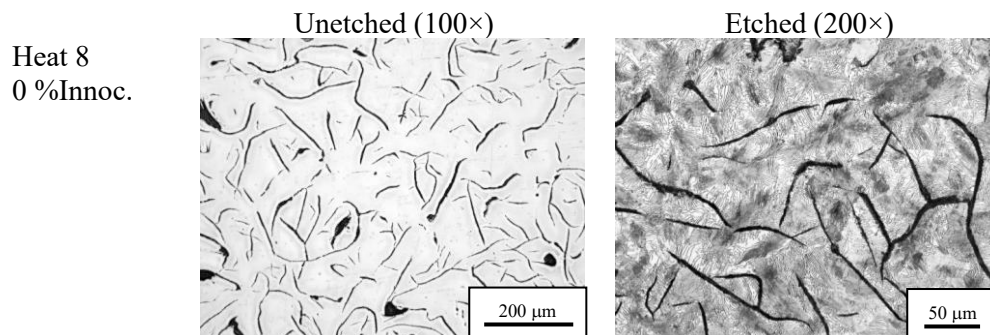
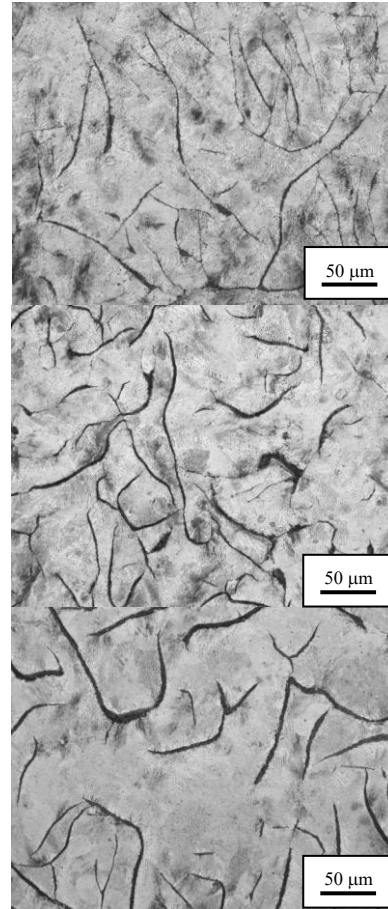
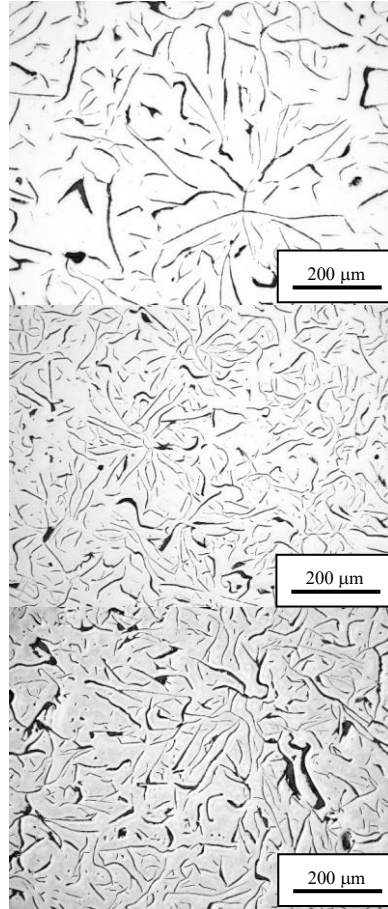


Figure 5 Percentage area of phases as a function of *G.P.* measured by image analysis.

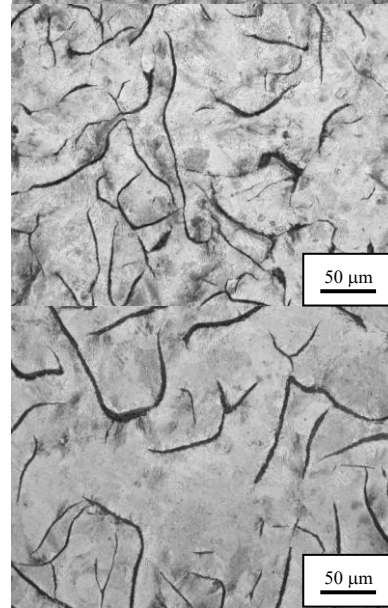
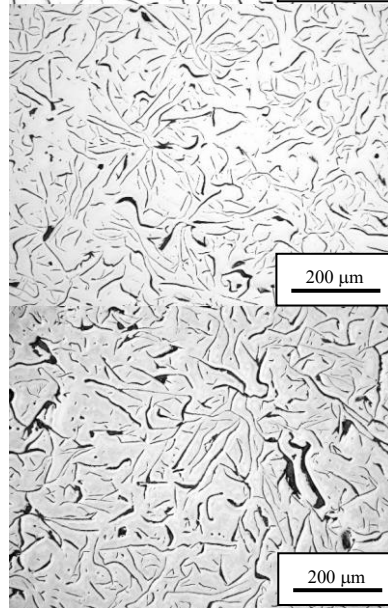
The microstructure of gray irons with various levels of inoculation are shown in Figure 6. The unetched microstructures demonstrate that increasing levels of inoculation results in finer graphite. The percentage of graphite in the microstructures was about the same in this series as the carbon equivalent was relatively unchanged. Furthermore, no ledeburite was found in all samples in this series. The etched microstructures show that pearlite is the dominant matrix phases. This was expected to as Mn was 0.38% promoting the pearlite formation. The percentage area of phases with different levels of inoculation is shown in Figure 7.



Heat 9
0.1 %Innoc.



Heat 10
0.2 %Innoc.



Heat 11
0.3 %Innoc.

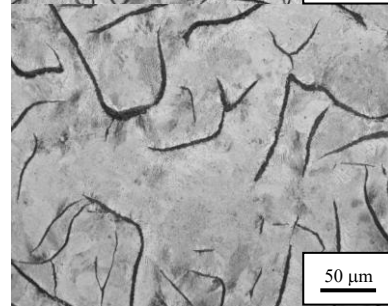
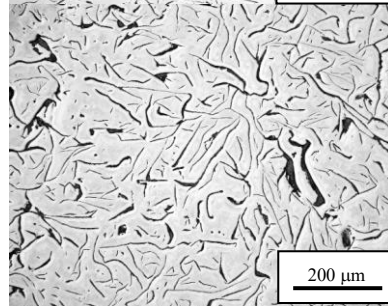


Figure 6 Selected OM micrographs of selected conditions of gray iron with varying inocuation levels (unetched, 100× and etched 200×).

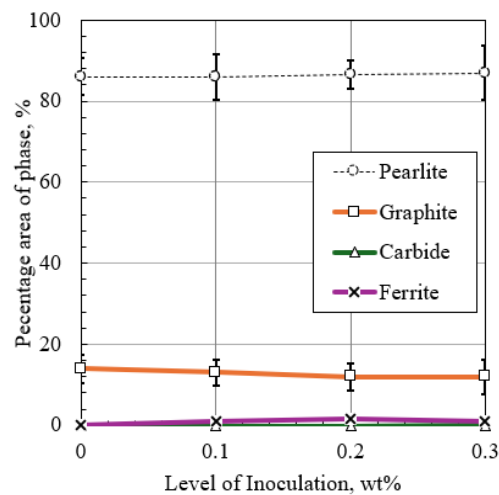


Figure 7 Percentage area of phases as a function of level of inoculation by image analysis.

Thermal Analysis and Linear Displacement Analysis (TA-LDA)

Thermal analysis is based on the change (and the rate of change) of temperature during the solidification process of cast iron which helps identify solidification events such as liquidus arrest, eutectic temperature, undercooling and recalescence. The Linear displacement analysis (LDA) relies on the principle of volumetric changes that occur during the solidification of cast irons due to formation of austenite and graphite which result in either expansion or contraction of the casting. Figure 8 and Table 4 demonstrate the example of cooling and displacement curves along with symbols and definitions associated with the further analysis.

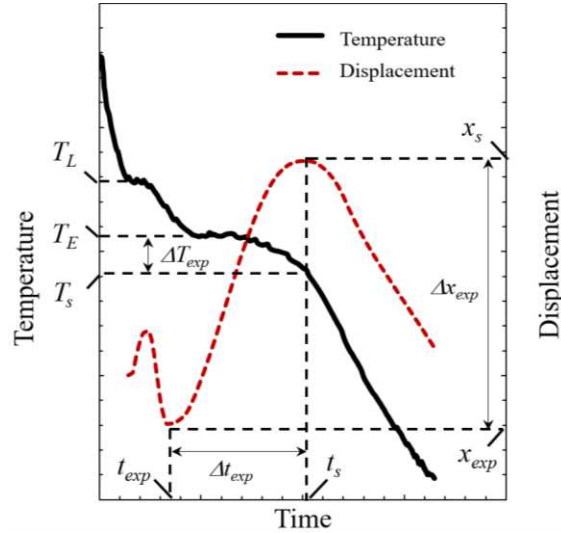


Figure 8 Example of cooling and displacement curves with symbols and definitions of the parameters for TA-LDA analysis.

Table 4 Symbols and definitions of the parameters for TA-LDA analysis.

Symbol	Definition	Unit
T_{exp}	Temperature at expansion starts	°C
x_{exp}	Location of expansion starts	mm
x_{shr}	Location of shrinkage starts	mm
x_s	Location of the end of solidification	mm
Δx_{exp}	Total expansion displacement ($x_{shr} - x_{exp}$)	mm
Δx_{shr}	Total shrinkage displacement ($x_s - x_{shr}$)	mm
t_{exp}	Time at expansion starts	s
t_{shr}	Time at shrinkage starts	s
t_s	Time at the end of solidification	s
Δt_{exp}	Total expansion time	s
Δt_{shr}	Total shrinkage time	s

Δt_{total}	Total solidification time	s
T_p	Pouring temperature	°C
T_{LA}	Temperature of liquidus arrest	°C
T_E	Equilibrium eutectic temperature	°C
T_{EU}	Temperature of eutectic undercooling	°C
T_{ER}	Temperature of eutectic recalescence	°C
T_S	Solidus temperature	°C

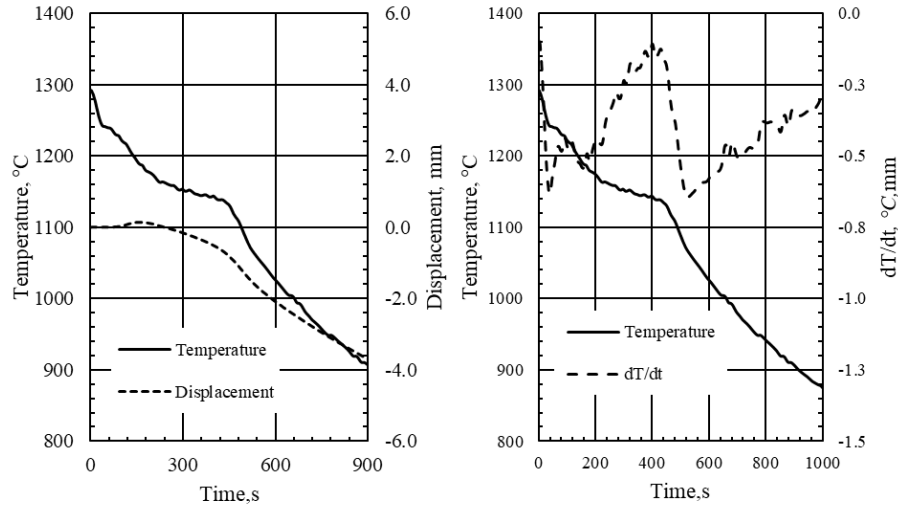
Effect of Graphitization Potential (G.P.) and Carbon Equivalent (CE)

Figure 9 shows the results for the TA-LDA analysis of gray irons with various *G.P.* and *CE*. For TA, the cooling rate is calculated and plotted along with the cooling curve. The cooling rate helps identify T_{LA} , T_{EU} and T_{ER} . It is seen that the higher Si resulted in larger proportion of the eutectic reaction due to increasing *CE* (less primary austenite). For LDA, the cooling curve is plotted along with the linear displacement curve. The value for displacement is notated as positive for expansion and negative for contraction. Typically, the LDA curve starts with contraction which corresponds to the formation of primary austenite due to its higher density compared to liquid iron. Next, the expansion occurs as the casting reaches the eutectic reaction. The metastable eutectic reaction (ledeburite) does not produce eutectic expansion unlike the stable eutectic reaction (austenite + graphite). This is because the formation of graphite creates the expansion through its lower density relative to the density of liquid iron. This behavior is seen in Heat 1 (0.02 %Si, *CE* = 3.47, *G.P.* = 6.93 °C). There was very little expansion seen in the LDA curve. Noted that the insignificant expansion can be a result from liquid movement generated by natural convection which is negligible.

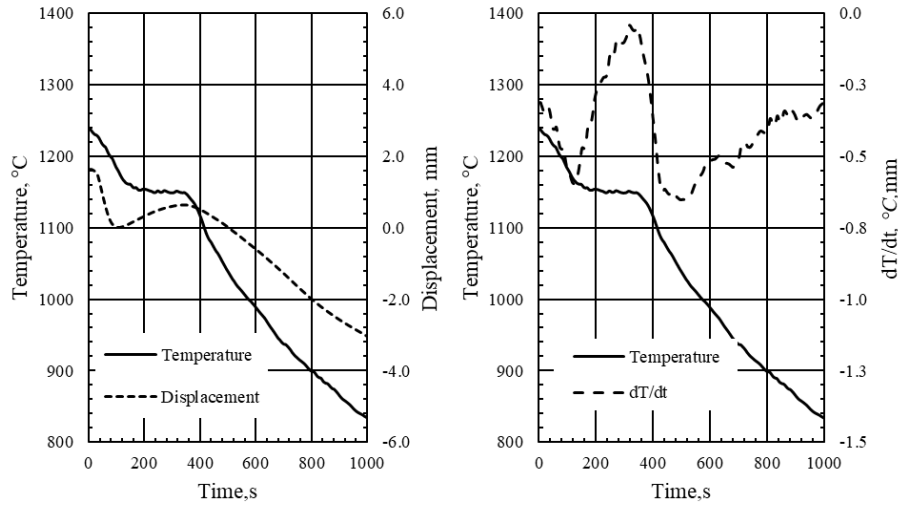
The eutectic expansion was clearly observed in all other heats (Figure 9b-f). As seen, the time at expansion starts (t_{exp}) are at the same time as T_{EU} is reached. This is expected as the eutectic reaction starts at T_{EU} and the expansion begins. Next, the expansion stops at the end of eutectic reaction (also the end of solidification) which is approximately when the maximum cooling rate at the end of solidification is. After the end of solidification, the contraction follows. This indicates that the apparatus captured this event consistently demonstrating the repeatability of the experiment. Overall, the transition from mottled to gray iron can be seen through the TA-LDA experiment. Increasing Si promotes the stable eutectic reaction (formation of eutectic graphite) observed by the greater total expansion displacement (Δx_{exp}) and total expansion time (Δt_{exp}). This is expected as increasing Si also increases the graphitization potential (*G.P.*) and carbon equivalent (*CE*).

Figure 10 illustrates the relationship between Δx_{exp} and graphitization potential (*G.P.*). Heat 7 exhibits an unusually high graphitization potential because of its extremely high carbon equivalent. It should be noted that carbon increases the carbon equivalent but does not directly contribute to the graphitization potential. As a result, a more distinct correlation is observed when graphitization potential is plotted against *CE*.

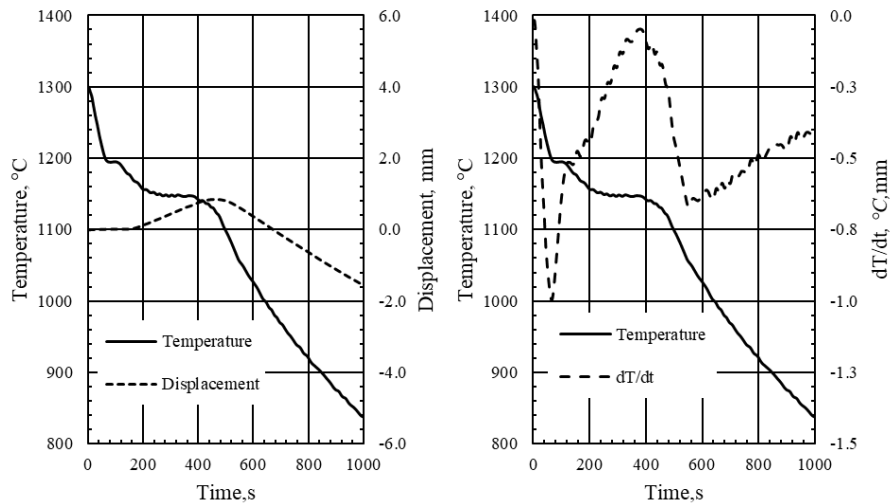
The influence of CE is demonstrated by the ratios of shrinkage time (Δt_{shr}) and expansion time (Δt_{exp}) to the total solidification time (Δt_{total}), as presented in Figure 11. With increasing CE , the proportion of shrinkage time decreases, whereas the proportion of expansion time increases, indicating that higher carbon equivalent promotes graphitization during solidification and enhances eutectic expansion. The results agree with Alonso et al. [2] that reported greater expansion under conditions promoting graphite formation.



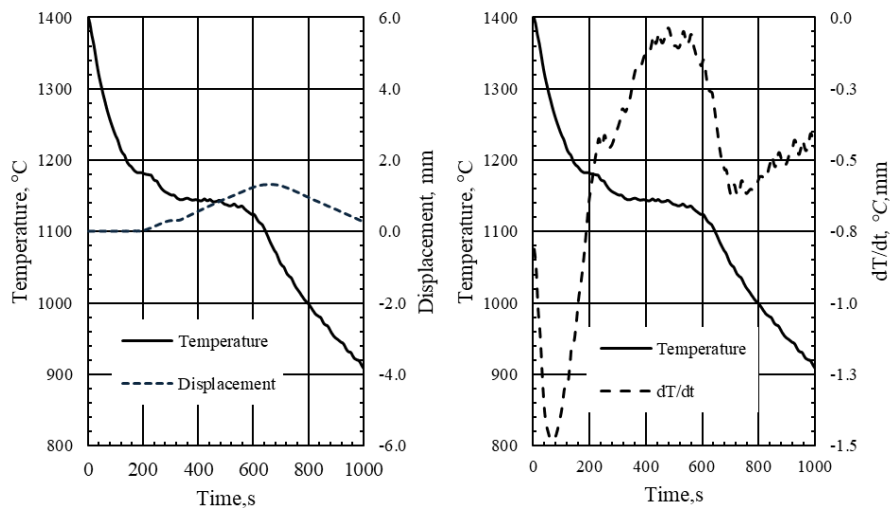
a) Heat 1, 0.02 %Si, $CE = 3.47$, G.P. = 6.93°C



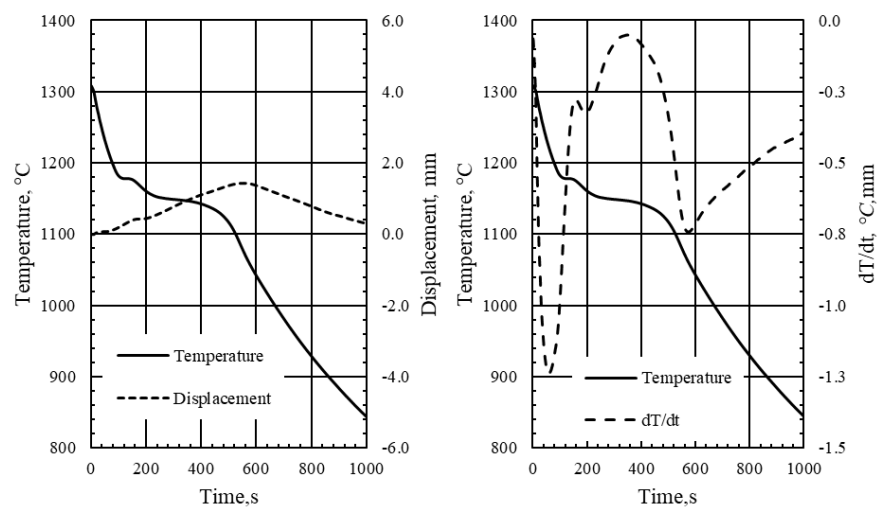
b) Heat 2, 0.48 %Si, $CE = 3.87$, G.P. = 16.03°C



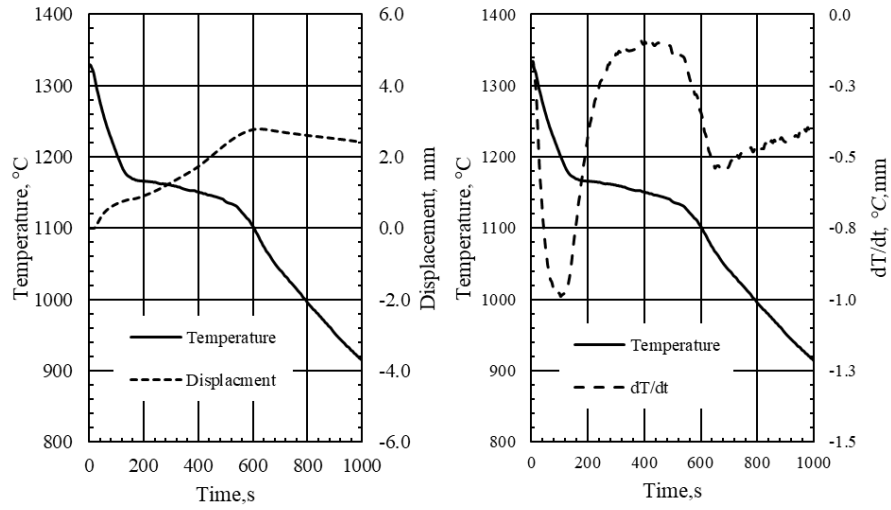
c) Heat 3, 0.95 %Si, CE = 4.03, G.P. = 23.45 °C



d) Heat 5, 1.80 %Si, CE = 4.26, G.P. = 41.48 °C



e) Heat 6, 2.06 %Si, CE = 4.37, G.P. = 45.73 °C



f) Heat 7, 1.78 %Si, CE = 5.59, G.P. = 42.69 °C

Figure 9 TA-LDA of gray irons with various carbon equivalents and graphitization potentials.

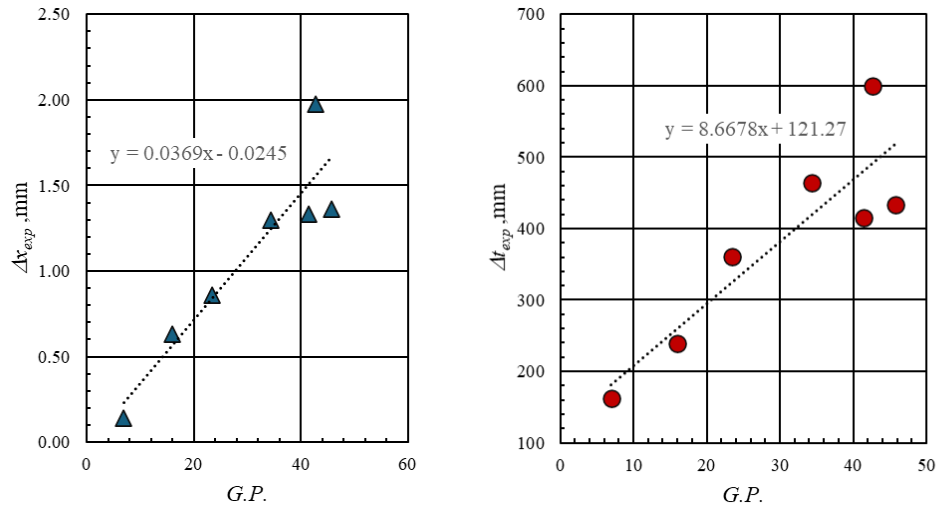


Figure 10 Relationship between the total expansion displacement (Δx_{exp}) and the graphitization potential (G.P.) for gray irons in Series 1 (Heat 1 to 7, without inoculation).

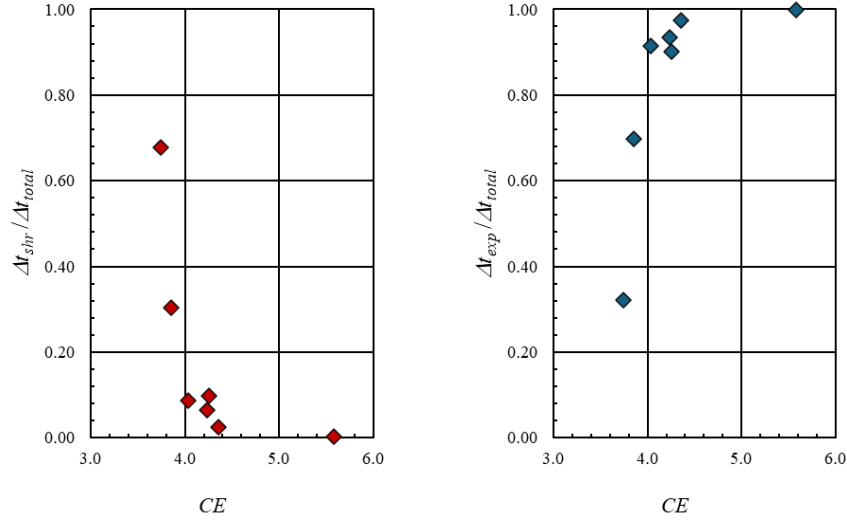


Figure 11 Effect of carbon equivalent (CE) on the ratios of shrinkage time (Δt_{shr}) and expansion time (Δt_{exp}) to the total solidification time (Δt_{total}) for gray irons in Series 1 (Heat 1 to 7, without inoculation).

Effect of levels of inoculation

The levels of inoculation in this study are 0, 0.1, 0.2 and 0.3% by weight of the melts. This is to reflect industrial practice as inoculation is usually conducted in the production of gray irons. Heat 8-11 were produced with comparable base compositions (CE 4.35-4.39) with different levels of inoculation. Figure 12 shows the displacement curves for gray irons in this experiment. It is seen that the total expansion displacements were in the range of 0.8-1.5 mm. Since the difference was quite small, the expansion parts of Displacement curves are superimposed in Figure 13. As seen, increasing levels of inoculation clearly increased the total expansion displacements and total expansion times. This is because the inoculation promotes the nucleation of eutectic cells resulting in greater eutectic expansion. This experiment also reflects the common knowledge of the industry that inoculation reduces the formation of the shrinkage porosity in the castings. In this study, there was no internal shrinkage porosity throughout the experiment. Presumably, the resin sand mold encased with steel jacket help contain expansion pressure compensating for the shrinkage in the test castings. This result demonstrates that CE alone cannot fully describe the expansion behavior of gray iron. At nearly constant CE , the effect of the graphite nucleation through inoculation changed both the magnitude and duration of eutectic expansion.

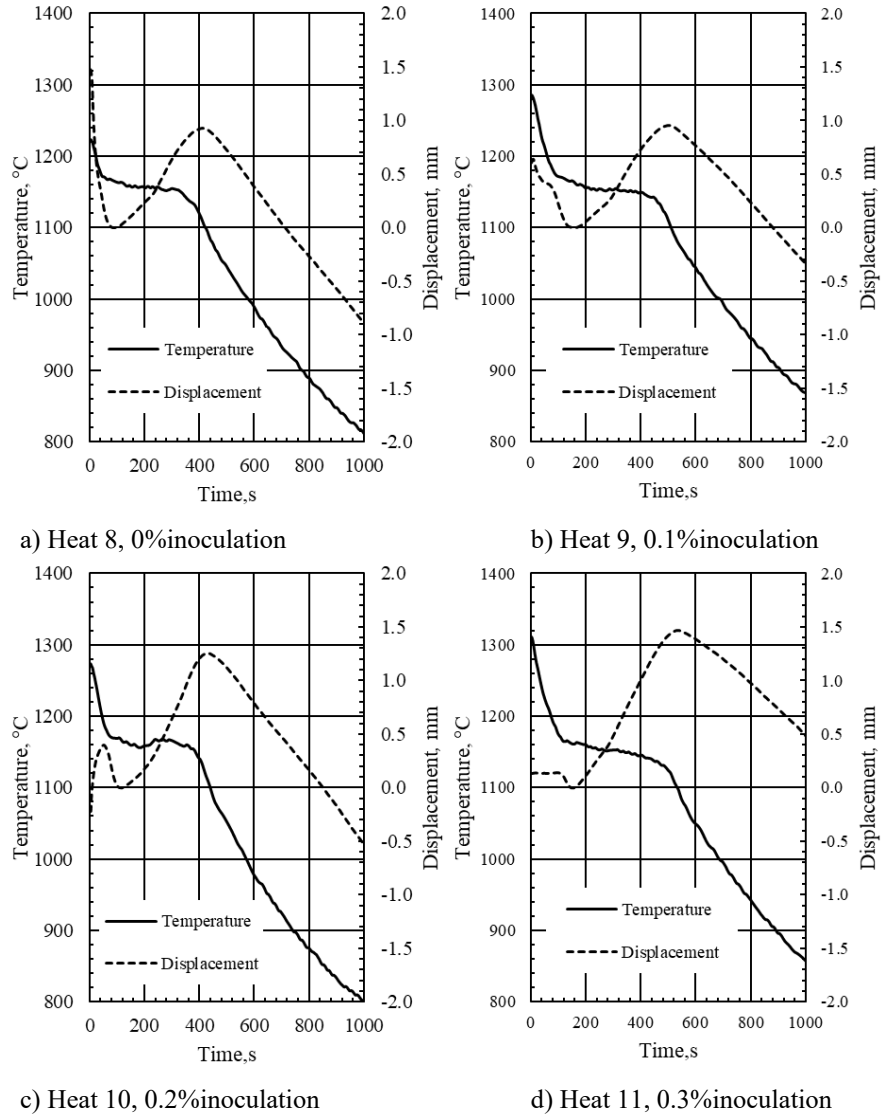


Figure 12 Displacement curves of gray irons in Series 2 (Heat 8 to 11, effect of inoculation)

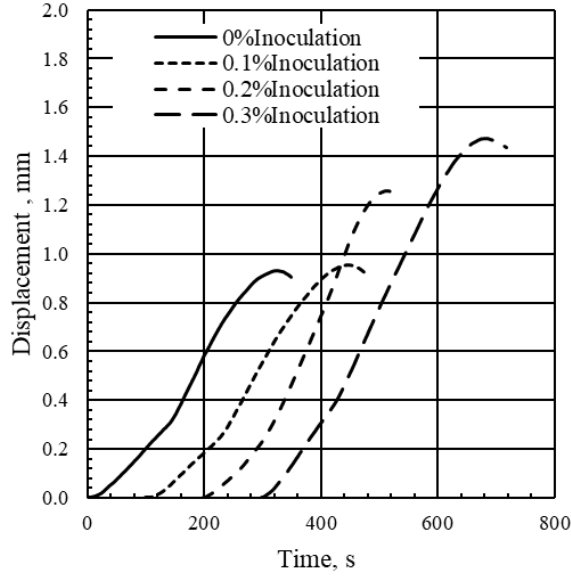


Figure 13 Comparison of the expansion parts of the displacement curves of gray irons with various inoculation levels (Series 2).

Correlation analysis

Based on the preceding analysis, correlation analysis was used to further evaluate the relationships among the parameters affecting solidification behavior. Table 5 presents the corresponding correlation coefficients, ranging from -1 to $+1$, where values closer to ± 1 indicate stronger linear relationships. Positive and negative values represent positive and negative correlations, respectively. The coefficients were calculated using Eq. 6, following Taylor [20].

$$r = \frac{\sum (x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum (x_i - \bar{x})^2 \sum (y_i - \bar{y})^2}}$$

Eq. 6

where r is the correlation coefficient, x_i and y_i are the individual values of the x - and y -variables, respectively, $\bar{x}$ and $\bar{y}$ are their corresponding mean values.

The correlation coefficients in Table 5 further support the relationships observed from the TA-LDA curves. The total expansion displacement (Δx_{exp}), shows strong positive correlations with Si ($r = 0.90$) and CE ($r = 0.88$). Similarly, the total expansion time, (Δt_{exp}), is strongly correlated with Si ($r = 0.92$) and CE ($r = 0.88$). These correlations indicate that increasing Si and CE favors the stable eutectic reaction resulting in long expansion time. The effect of CE on the total expansion displacement and time of gray irons in both series is shown in Figure 14. As seen, the total expansion displacement and time both increased with increasing CE. Heat 7 shows the highest values in both displacement and time due to its very high CE (CE = 5.59). Noted that the trend is clearer in the Series 1 which varies CE. In Series 2, the CEs were kept at the same level, therefore, the trend was not as clear as in the Series 1.

Also, the Δx_{exp} and Δt_{exp} shows very strong correlation ($r = 0.92$) as shown in Figure 15. This suggests that the magnitude of eutectic expansion is closely related to the duration of the expansion stage. In other words, conditions that allow the graphite-forming eutectic reaction to continue for a longer period generally produce a larger displacement. This observation is consistent with the TA-LDA curves in Figure 9, where increasing Si and CE resulted in both longer expansion periods and greater expansion displacement.

Table 5 Correlation analysis between parameters in Series 1.

	T_L	C	Si	CE	Δx_{exp}	Δt_{exp}	ΔT_{exp}	t_s	T_s
T_L	1.00								
C	0.43	1.00							
Si	-0.92	0.29	1.00						
CE	-0.95	0.92	0.65	1.00					
Δx_{exp}	-0.91	0.64	0.90	0.88	1.00				
Δt_{exp}	-0.97	0.36	0.92	0.88	0.92	1.00			
ΔT_{exp}	-0.43	0.06	0.30	0.19	0.17	0.25	1.00		
t_s	-0.60	0.48	0.44	0.57	0.57	0.65	0.52	1.00	
T_s	0.12	-0.10	-0.04	-0.09	-0.16	-0.23	0.33	-0.47	1.00
Δx_{shr}	0.91	-0.31	-0.98	-0.66	-0.92	-0.94	-0.31	-0.54	0.09

In contrast, the shrinkage displacement, (Δx_{shr}), shows strong negative correlations with Si ($r = -0.98$), Δx_{exp} ($r = -0.92$) and Δt_{exp} ($r = -0.94$). These results demonstrate the competing effects of contraction and graphite expansion during solidification. At low Si and low $G.P.$, a larger proportion of solidification occurs through primary austenite and/or the metastable eutectic reaction, resulting in greater contraction. As Si increases, the stable eutectic reaction becomes increasingly favorable and graphite formation compensates the contraction. Therefore, conditions associated with greater eutectic expansion simultaneously exhibit lower shrinkage displacement.

The liquidus temperature, (T_L), also shows strong negative correlations with Si ($r = -0.92$), CE ($r = -0.95$), Δx_{exp} ($r = -0.91$) and Δt_{exp} ($r = -0.97$). This is expected as lower CE increases the liquidus temperature, therefore, the liquidus arrest in TA is observed at higher temperature. Consequently, decreasing CE also decreased the eutectic expansion seen through Δx_{exp} and Δt_{exp} . On the other hand, ΔT_{exp} and T_s generally show weaker correlations with composition and expansion parameters. This suggests that the magnitude of eutectic expansion is governed by the relative amounts and duration of the solidification reactions than by the absolute temperatures at which expansion starts or solidification ends. Overall, the correlation analysis confirms that Si and CE strongly influence the balance between contraction and expansion during solidification, primarily through their effects on graphitization and the relative portion of eutectic solidification.

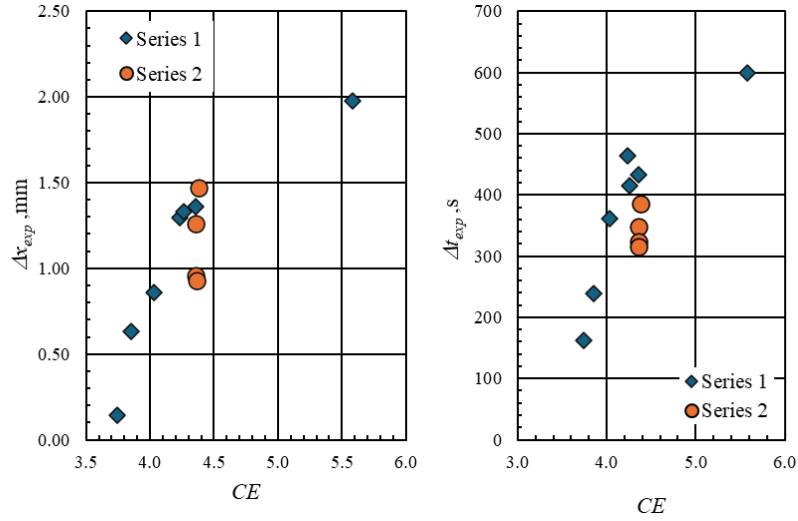


Figure 14 Effect of CE on the total expansion displacement and time of gray irons in both series.

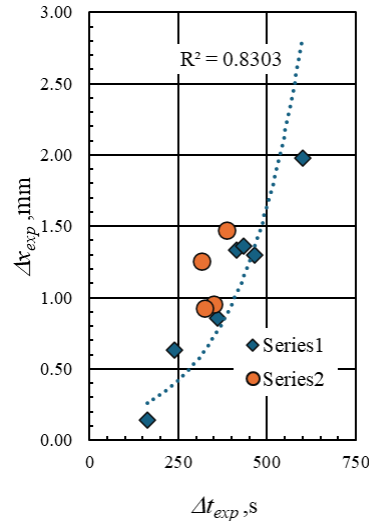


Figure 15 Relationship between the total expansion displacement and total expansion time of gray irons in both series.

Casting dimensional change

The effect of CE and G.P. on the dimensional change of casting after solidification is also important for industrial practice. Normally, the patterns are made with allowances such as machining allowance, shrinkage allowance and distortion allowance. Among these allowances, the shrinkage allowance is the most important as it usually dictates the design of the subsequent processes like machining and boring. The shrinkage allowance in gray iron is expected to depend on CE and G.P. because the volumetric change is dictated by the density change. For hypoeutectic compositions, the initial formation of primary austenite causes contraction because austenite has a higher density than the liquid. As the temperature decreases to the eutectic, graphite and austenite form simultaneously and produce expansion. The final dimensional change therefore represents the balance between these two competing mechanisms. After solidification, the castings cool down to room

temperature and continue to contract. Noted that the eutectoid reaction also contributed to the final dimension but with lesser degrees. At the room temperature, the castings are normally smaller than the patterns. The shrink rate also depends on *CE* and *G.P.*

Increasing Si and CE shifts this balance toward expansion due to the reduction of the initial contraction by austenite formation along with the increase in eutectic expansion. Therefore, gray irons with higher Si and CE have greater proportion of eutectic reaction. In addition, gray irons with low G.P. tend to shrink at higher rate due to the carbide formation (lack of graphite formation). Figure 16 shows the percentage change in diameter of castings. The negative numbers indicate shrink in diameter. As seen, increase *CE* and *G.P.*, reduced the shrinkage. Noted that Heat 7 (black dot in Figure 16b) shows lowest change in diameter due to its very high carbon with lower G.P. The percent of shrinkage is comparable to the recommended value for gray iron used by foundrymen (e.g. 10 mm / 1000 mm or 1.0%). However, this study suggests that the shrinkage allowance can be more precisely calculated by considering *CE*. On the other hand, levels of inoculation did not have significant effect on the dimensional change.

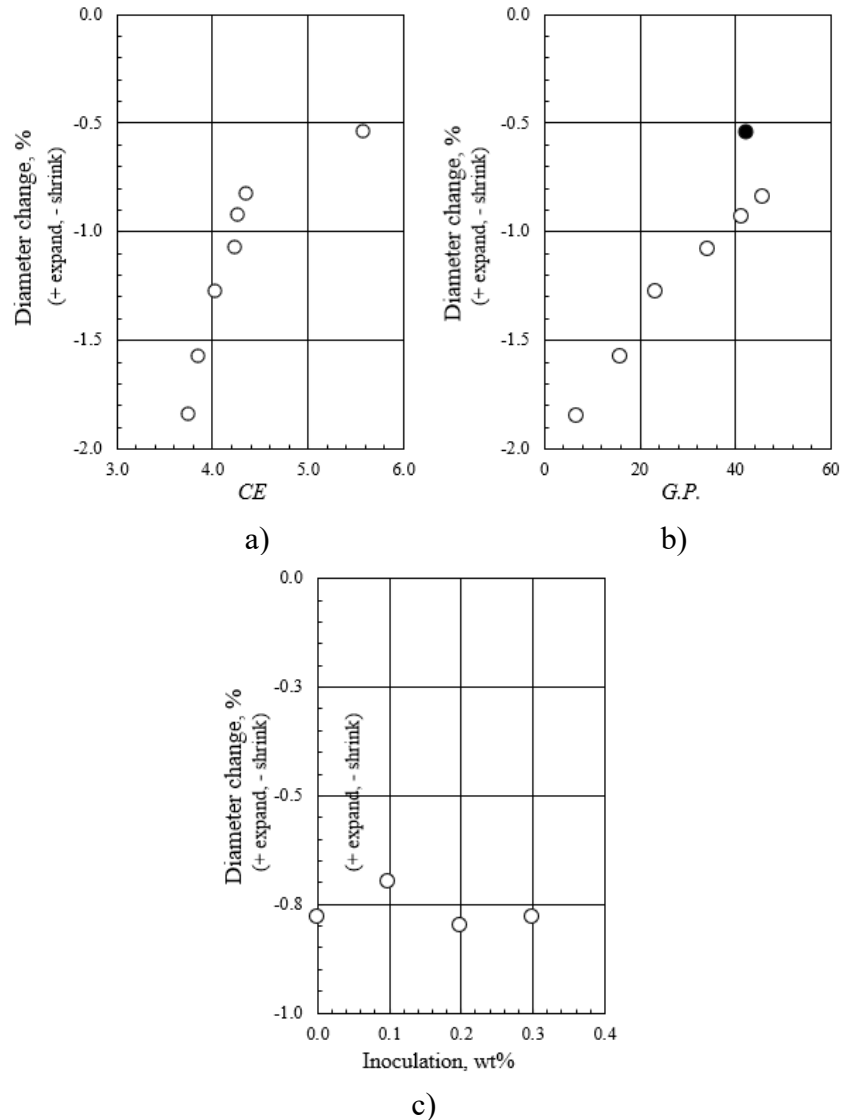


Figure 16 Effect of graphitization potential and inoculation levels on the diameter change of the test casting; a) carbon equivalent; b) graphitization potential; c) percent inoculation.

Density change

The density of gray iron after solidification is expected to reflect the relative amounts of graphite, ferrite, pearlite, carbide and internal porosity. Graphite has lower density than the matrix; therefore, increasing CE tends to decrease the density of the casting. Conversely, carbide formation suppresses graphite precipitation resulting in higher density.

Figure 17 shows the effect of CE on casting density. As seen, higher CE reduced the density as expected. Within the composition and processing range investigated in this study, the measured density can be approximated by

$$\text{Density} = -399.06 \text{ CE} + 8921.3 \quad \text{Eq.7}$$

where density is in kg/m^3 . On the other hand, the levels of inoculation did not show an effect on density.

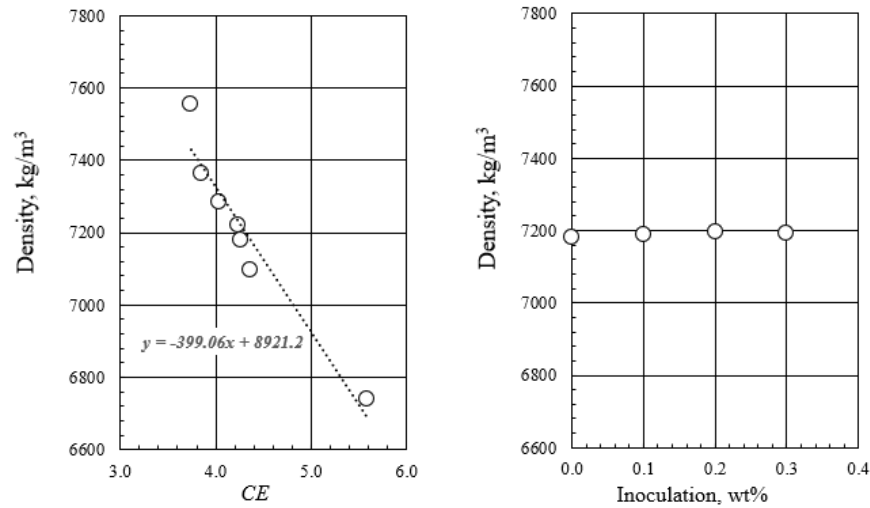


Figure 17 Effect of graphitization potential and inoculation levels on density of the test castings; a) carbon equivalent; b) percent inoculation.

Conclusions

This study investigated the effects of Si, graphitization potential ($G.P.$), carbon equivalent (CE) and inoculation on the eutectic expansion behavior of gray cast iron using combined Thermal Analysis and Linear Displacement Analysis (TA-LDA). The main conclusions are summarized as follows:

1. The developed TA-LDA apparatus successfully captured the contraction and expansion at different stages of gray iron solidification. The data from the TA-LDA can be compared between experiments showing clear trends and correlations between parameters.

2. Increasing Si increased the graphitization potential and promoted stable eutectic solidification. At low *G.P.*, carbide formation was observed and eutectic expansion was limited. Increasing *G.P.* suppressed carbide formation and resulted in greater expansion displacement and longer expansion time.
3. Increasing *CE* reduced the shrinkage and increased the eutectic expansion seen through the greater total expansion displacement and longer total expansion time. The highly hypereutectic iron (*CE* = 5.59) exhibited Type-C graphite and the greatest expansion behavior, reflecting the additional contribution of primary graphite formation.
4. Correlation analysis shows strong relationships between composition and expansion behavior. Total expansion displacement showed strong positive correlations with Si ($r = 0.90$) and *CE* ($r = 0.88$), while expansion time showed similarly strong correlations with Si ($r = 0.92$) and *CE* ($r = 0.88$). In contrast, shrinkage displacement was strongly negatively correlated with Si ($r = -0.98$), demonstrating the competing effects of austenite-related contraction and graphite-related expansion.
5. Increasing the inoculation levels increased both the total expansion displacement and expansion time despite the relatively constant *CE*. However, increasing the inoculation levels did not have significant effect on dimensional change and density of the castings.

Overall, eutectic expansion in gray iron is governed by the combined effects of carbon equivalent, graphitization potential, and inoculation. The TA-LDA approach developed in this study provides a useful method for quantifying these effects and can provide experimental data for understanding feeding behavior and improving the prediction of solidification shrinkage in gray iron castings.

Acknowledgement

This work was financially supported by the SUT Research and Development Fund, Suranaree University of Technology, Thailand.

Conflicts of interest

We declare that this manuscript is original, has not been published before and is not currently being considered for publication elsewhere.

References

1. Queirós, R., Domeij, B. & Diószegi, A. Unraveling Compacted and Nodular Cast Iron Porosity: Case Studies Approach. *Inter Metalcast* **18**, 1811–1830 (2024). <https://doi.org/10.1007/s40962-023-01149-9>
2. G. Alonso, D.M. Stefanescu, R. Suarez, A. Loizaga, G. Zarrabeitia, *Int. J. Cast Met. Res.* **27**, 87–100 (2014). <https://doi.org/10.1179/1743133613Y.00000000085>
3. A. Tadesse, H. Fredriksson, *Int. J. Cast Met. Res.* **30**, 159–170 (2017). <https://doi.org/10.1080/13640461.2016.1277851>

4. G. Alonso, A. Loizaga, G. Zarrabeitia, D.M. Stefanescu, Kinetics of Graphite Expansion during the Solidification of Lamellar and Spheroidal Graphite Iron. *Trans. Am. Foundry Soc.* **122**, 237-248 (2014)
5. L. Stuewe, A.P. Tschiptschin, W.L. Guesser, R. Fuoco, Influence of chromium and molybdenum in solidification and shrinkage defects for high resistance grey iron alloys, in *Proceedings of the 10th International Symposium on the Science and Processing of Cast Irons*, Mar del Plata (2010)
6. W.A. Schmidt, E. Sullivan, H.F. Taylor, Riserling of gray iron. *Trans. Am. Foundrymen's Soc.* **62**, 70–77 (1954)
7. P. Svidró, A. Diószegi, *Int. J. Cast Met. Res.* **27**, 26–37 (2014).
<https://doi.org/10.1179/1743133613Y.00000000075>
8. Y. Zou, Y. Hayashi, H. Kojima, K. Yamazaki, H. Nakae, Influence of mold material and CE value on shrinkage of spheroidal graphite cast iron, in *Proceedings of the 70th World Foundry Congress*, Monterrey, Nuevo Leon, Mexico, Paper 11 (2012)
9. D.M. Stefanescu, L. Dinescu, S. Crăciun, M. Popescu, Production of vermicular graphite cast-irons by operative control and correction of graphite shape, in *Proceedings of the 46th International Foundry Congress*, Madrid, Spain, pp. 37–37/15 (1979)
10. M. Degois, in *The Metallurgy of Cast Irons*, ed. by B. Lux, I. Minkoff, F. Mollard (1975), p. 741
11. R. Hummer, in *The Physical Metallurgy of Cast Iron*, ed. by H. Fredriksson, M. Hillert (North-Holland, New York), pp. 213–222
12. Z. Gedeonova, S. Bodi, J. Dúl, G. Nándori, L. Vigh, *Mater. Sci. Forum* **215–216**, 391–398 (1995)
13. P. Mrvar, M. Trbižan, J. Medved, Investigation of cast iron solidification with dilatation analysis. *Kovine Zlitine Tehnologije* **33**, 45–49 (1999)
14. M. Chisamera, I. Riposan, S. Stan, P. Toboc, T. Skaland, D. White, *Int. J. Cast Met. Res.* **24**, 28–36 (2011). <https://doi.org/10.1179/136404610X12816241546618>
15. D.M. Stefanescu, M. Moran, S. Boonmee, Use of combined liquid displacement and cooling curve analysis in understanding the solidification of cast iron. *Trans. Am. Foundry Soc.* **120**, 365–374 (2012)
16. S. Boonmee, A. Utsajai, On the kinetics of the eutectic expansion in cast irons. *AIP Conf. Proc.* **1986**, 020011 (2018)
17. J. Lacaze, J. Sertucha, U. de la Torre, Density change upon solidification of silicon cast irons. *Inter. Metalcast.* **17**, 1493–1506 (2023). <https://doi.org/10.1007/s40962-022-00868-9>
18. J. Dorula, D. Kopyciński, E. Guzik, A. Szczesny, *Materials* **15**, 6273 (2022).
<https://doi.org/10.3390/ma15186273>
19. A.A. Zhukov, *Metal Forum* **2**, 127–136 (1979)
20. J.R. Taylor, *An Introduction to Error Analysis: The Study of Uncertainties in Physical Measurements* (University Science Books, Sausalito, CA, 1997), p. 217