

DENSITY AND SURFACE TENSION OF MOLTEN CAST IRONS

P. Fima * and N. Sobczak

Institute of Metallurgy and Materials Science, Polish Academy of Sciences, Krakow, Poland

(Received 13 April 2021; accepted 03 September 2021)

Abstract

Computer-aided development of liquid-assisted metallurgical processes requires reliable basic data for the molten materials, including thermophysical properties such as density, surface tension, and viscosity. Cast irons belong to the group of Fe-C alloys of practical importance due to their good technological and utility properties, yet experimental thermophysical data of cast irons in the literature are scarce. In this study, the density and surface tension of three compacted graphite cast iron alloys were measured by the sessile drop method in contact heating mode in the temperature range of 1473 – 1723 K with polycrystalline alumina as a substrate. The drop profile images were recorded both during heating and subsequent cooling regimes. At 1473 K, the density values of the studied compacted graphite irons are between 6.66 and 6.69 g·cm⁻³, whereas surface tension values are between 1130 and 1510 mN·m⁻¹. The density decreases with increasing temperature, while surface tension dependence on temperature is less obvious. The obtained results are compared to the available literature data and analyzed taking into account chemical interaction of liquid cast irons with the substrate material.

Keywords: Compacted graphite iron; Density; Surface tension; Sessile drop

1. Introduction

Computer simulation is a fast and cost-effective approach in materials engineering not only for understanding different phenomena and materials behaviors but also to control and optimize technological processes in order to manufacture the defect-free products of desired structure and corresponding advantageous properties. Constant progress in the development of software for modeling of liquid-assisted metallurgical processes such as metal casting, solidification, refining, filtration, removal of solid inclusions, synthesis of metal-ceramic composites and joining dissimilar materials by welding, brazing, and soldering requires reliable basic data of molten materials. Such data of interest include thermophysical properties: density (ρ), surface tension (σ), and viscosity (η) [1].

Whilst cast irons are a group of the oldest and still the most widely used alloys in metal casting history due to beneficial combination of their low cost, good castability and utility properties [2,3], yet the literature survey shows extreme scarcity of experimental thermophysical data of cast irons and only limited experimental data can be found in open literature [4-7]. This is understandable considering methodological problems due to high temperatures

involved and hard to avoid risk of reactivity between a molten alloy and a refractory material used as a container or a substrate in container or substrate assisted techniques for thermophysical properties measurements.

Cast irons belong to a family of ferrous alloys containing high amount of carbon (2 - 6.67 wt%), as compared to the steels of maximum amount below 2 wt% C. For these Fe-C alloys, their chemical composition and molten metal treatment have significant effects on the type, chemistry, and morphology of precipitates formed with carbon. There are two main groups of cast irons, i.e. those in which carbon is present in cementite phase (Fe₃C) belong to a group of “white” cast irons while the others have graphite precipitates and thus are named “grey” cast irons. Moreover, by applying molten metal engineering approach involving different molten metal treatments, graphite phase can be nucleated in dissimilar shapes. The flake-like precipitates of elongated shape are typical for conventional grey cast iron, classified as lamella graphite iron (LGI). Nearly-spherical (nodular) graphite precipitates are formed in spheroidal graphite cast iron (SGI), also known as ductile iron. Worm-like stubby graphite precipitates having rounded edges occur in compacted cast iron (CGI), also called

*Corresponding author: p.fima@imim.pl



vermicular cast iron [2,3].

Since not only the amount of graphite but first its morphology significantly influences the properties and performance of cast iron components, many studies were focused on understanding factors affecting the nucleation and growth of graphite phase from Fe-C melts (e.g. [3, 8-11]). Shi et al. [12] made an attempt to establish experimentally the specific relationship between the surface tension of cast iron and the graphite shape. Based on comparative measurements of surface tensions of selected cast iron alloys by modified maximum bubble pressure method versus structural examination of solidified samples, Shi et al. [12] distinguished the surface tension values that correspond to different shapes of graphite precipitates and proposed to use this approach for effective, convenient, and rapid monitoring of quality of molten metal in metal casting practice. For cast iron alloys containing 3.7-4.2 C, 2.2-3.0 Si, 0.3-0.5 Mn, <0.06 P, <0.02 S, <0.002 Ca, and Re>0.0035 (wt%), produced from Pig iron Z14 modified with different amounts of modifying agent 1RETiMg10-5, Shi et al. established the following relationships between surface tension values and graphite morphology:

for $\sigma > 990 \text{ mN}\cdot\text{m}^{-1}$ – flake graphite,

for $990 < \sigma < 1108 \text{ mN}\cdot\text{m}^{-1}$ – flake and vermicular graphite,

for $1108 < \sigma < 1283 \text{ mN}\cdot\text{m}^{-1}$ – vermicular graphite,

for $1283 < \sigma < 1385 \text{ mN}\cdot\text{m}^{-1}$ – vermicular and nodular graphite,

for $\sigma > 1385 \text{ mN}\cdot\text{m}^{-1}$ – nodular graphite.

However, more experimental work should be done in order to understand factors affecting surface tension of molten cast irons. Such information is of scientific and of practical importance for both the prediction of graphite nucleation, and to produce final cast components of high-quality and required properties. Literature data for pure Fe and its binary alloys [13] show that the main factors responsible for scattering of experimental measurements are: 1) testing methods and procedures, 2) atmosphere used for measurements, and 3) impurities, particularly the presence and amount of surface-active elements such as oxygen, sulphur, phosphorous, e.g. only a few ppm of oxygen are sufficient to decrease the surface tension of pure iron by more than 30% [13].

In this work, the effort has been made for the first time to estimate experimentally the temperature dependencies of density and surface tension of three molten compacted cast iron alloys by the sessile drop

method under both heating and cooling regimes.

2. Experimental

Three hypereutectic Compacted Graphite Iron (CGI) alloys, named CGI-0, CGI-3, and CGI-4 (Table 1), were produced in the Foundry Research Institute (Krakow, Poland), following the procedure described in [14]. For all alloys, the concentrations of C, Si, Mn, P, S, and Mg are fairly similar. The CGI-3 and CGI-4, however, contain Mo, Cu, V, Sn, and Sb. In the CGI-4, the concentrations of Mo and Cu are nearly double of that in CGI-3. For measurements, the cast iron samples were cut from large castings to first get pieces with cubic shape of approx. $5 \times 5 \times 5 \text{ mm}$ dimensions. These had four edges filed to get a more cylindrical shape, while the lower edges of each sample were undercut (see Fig. 1a in [16]) to reduce its contact area with a substrate because such a shape of the solid sample helps the formation of a symmetrical drop and facilitates the identification of the base line position, which in turn contribute to the reduction of measurement errors. The resulting samples had masses of 0.201 - 0.367 g and below 0.05 cm^3 in volume.

For measurements of surface tension and density of molten CGI samples, the images recorded in the sessile drop tests, carried out in works [15,16] for investigation of melting, wetting and solidification behaviors of selected compacted cast irons, were used. All the tests were performed using contact heating mode [17], in the temperature range of 1473 – 1723 K. Before wetting studies, all the alloys were subjected to DSC study on cooling and heating at a rate of 10 K/min and the melting temperature was known. The results were close to CGI-0 alloy [14] due to the similar composition and they were used for selecting the temperature range in surface tension measurements. All of the alloys are fully molten below 1473 K (endset of melting peak below 1453 K on heating). From DSC and the difference between the endset of melting peak and the onset of freezing peak the supercooling could be estimated as 35 K. Nevertheless, in the sessile drop measurements, we deliberately started and finished our experiment well above melting temperature of a respective alloy.

For these tests, commercial polycrystalline alumina substrates ($\alpha\text{-Al}_2\text{O}_3$ of 99.7% purity and open porosity below 3 vol.%) of a cylindrical shape (18 mm in diameter and 5 mm high), produced by Ceramit

Table 1. Chemical composition of as-cast CGI samples (wt%, Fe – bal.)

Sample	C	Si	Mn	P	S	Mg	Mo	Cu	V	Sn	Sb
CGI-0	3.70	2.30	0.44	0.054	0.015	0.017	-	-	-	-	-
CGI-3	3.80	2.45	0.45	0.045	0.020	0.020	0.27	0.40	0.25	0.05	0.010
CGI-4	3.65	2.50	0.55	0.045	0.020	0.025	0.5	0.75	0.28	0.10	0.05



(Poland), were used. The surface roughness of the Al_2O_3 substrates was $R_a = 150 \pm 20$ nm. Before measurements, the substrates were ultrasonically cleaned in isopropyl alcohol and heated in air for 30 min at 1273 K. The sessile drop tests were carried out in the experimental complex for high temperature studies of liquid metals and alloys [18,19]. Directly before measurements, each CGI sample was mechanically and ultrasonically cleaned in isopropyl alcohol, placed on alumina substrate and locked in vacuum chamber equipped with turbomolecular pump and tantalum heating element. The vacuum chamber was evacuated to 2×10^{-6} mbar or better, then CGI sample/substrate couple was heated at 15 K/min rate. At a temperature of about 773 K, a flow of high purity (99.9992 %) Ar gas was gradually introduced into the vacuum chamber while the maximum Ar gas pressure in the chamber did not exceed 900 mbar. It should be highlighted that surface tension measurements of high temperature alloys, especially molten cast irons, are accompanied with many methodological problems. Therefore, the pressure level was selected experimentally taking into account as follows. For keeping chemical composition of alloy samples constant during testing, the evaporation of alloying additions and impurities should be avoided or at least significantly suppressed. In order to meet these requirements, high temperature tests are performed in non-reactive atmosphere using either flowing gas procedure or static gas procedure. The last one is more effective, but it is more difficult to meet the specific features of the design of ultra-high-vacuum (UHV) device used, such as the design of sealing system demanding work in pressure lower than atmospheric pressure, particularly during heating to high experimental temperature. The heating rate was maintained until the temperature reached 1723 K. After 15 min of isothermal heating at 1723 K, the sample/substrate couple was cooled at 20 K/min

cooling rate. Figure 1 illustrates temperature vs time plot of representative experiment. In the course of the whole experiment, a drop silhouette images were recorded with high-speed high-resolution CCD camera at a rate of 10 fps (frames per second) during heating and isothermal stage, and 1 fps during cooling stage, together with corresponding temperature and time. This allowed to pick a set of images at 50 K interval between 1473 K and 1723 K, recorded both on heating and cooling.

Density and surface tension were determined from the collected drop images following the procedure outlined in [20]. First, a set of coordinates were assigned to each drop's meridian profile. Such a set of coordinates was first used to calculate sample's density based on the assumption of drop's axial symmetry, as it was outlined in [21]. Finally, with computer program utilizing the algorithm proposed by Rotenberg et al. [22], the same set of coordinates and the density determined in previous step were used to calculate the surface tension. For each temperature, a set of 4 first images were analyzed and standard deviation of the determined properties (i.e., density and surface tension) were estimated. From selected heating and cooling rates and corresponding recording rates, it is expected that maximum temperature difference between the 1st and 4th images is about 0.13 K during heating and 2.26 K during cooling. Where feasible, the data were fitted with linear regression to obtain the dependence of density on temperature. In the case of isothermal heating at 1723 K, the images recording at 0, 7.5 and 15 min were analyzed.

3. Results and discussion

Figure 2 illustrates the density dependence on temperature for molten compacted graphite irons CGI-0, CGI-3, CGI-4. Data recorded on heating are represented with diamonds, data recorded on cooling with triangles, and data recorded in the middle of isothermal time are represented with squares.

For all three CGI samples, the density decreases with increasing temperature, the data are close while the coefficients of temperature dependence (Table 2) are similar. This tendency takes place in both heating and cooling modes. However, the data recorded on cooling do not reproduce the data collected on heating and the maximum difference reaches 4 % in the case of CGI-0 at 1453 K. While in the case of CGI-0 the data recorded on cooling are up to 4 % higher than the data recorded on heating, it is the opposite in the case of CGI-4 where the data recorded on cooling are up to 3.5 % lower than the data recorded on heating. The possible explanation for these discrepancies is discussed later, after comparison of the results of this study with those reported in previous investigations.

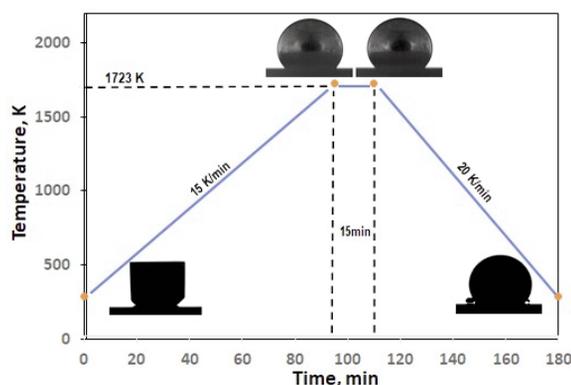


Figure 1. Plot of the temperature vs time in the course of experiment. Inserts illustrate representative images of CGI-0 drop at RT before heating, during holding at 1723 K (left: $t = 0$ min; right: $t = 15$ min) and after testing and cooling to RT

The experimentally measured density data for molten cast irons are scarce in literature [4-6]. Recently, Hellstrom et al. [6] employed dilatometric method to study density and thermal expansion of lamellar cast irons with carbon content ranging from 2.33 to 3.8 wt% and silicon content between 1.68 and 2.11 wt%, over rather narrow temperature range (90-130 K above liquidus). Two of the alloys that they

studied have carbon content similar to the present CGI samples, namely 3.8 and 3.63 wt%, but lower silicon content, respectively 1.74 and 1.68 wt%. The densities of the abovementioned alloys at liquidus temperature reported in [6] are $6.93 \text{ g}\cdot\text{cm}^{-3}$ at 1420 K and $6.95 \text{ g}\cdot\text{cm}^{-3}$ at 1440 K, respectively. It should be noted that since numerical data at liquidus temperature were not presented in [6], the above density values were digitized from respective figure. If we extrapolate the present density data determined on heating (Fig. 1) below 1473 K, it is clear that density of CGI-0 is lower than data of [6]. This was to be expected since the sample CGI-0 has higher silicon content.

Kawai et al. [4] applied the sessile drop method to measure the density of Fe-C-Si alloys with carbon content 1-3 wt% and silicon content 1-10 wt%. In the case of all the Fe-C-Si alloys studied [4], the density decreases with increasing temperature. The density of Fe-3C-2Si (wt%) [4], the composition of which is relatively close to the present CGI-0 alloy, is $7.045 \text{ g}\cdot\text{cm}^{-3}$ at 1473 K, which is 3.6% higher than the density of CGI-0 alloy recorded on heating. Burtsev et al. [5] measured the density of molten cast iron containing 3.6 wt% of carbon and 2.8 wt% of silicon with the use of a large drop method. As illustrated in Fig. 2, their results are lower than the present data for CGI-0. In general, as pointed out in [23,24], the density of liquid binary Fe-C alloys decreases with temperature as well as with the increasing carbon content. Similarly, an increasing silicon content in liquid binary Fe-Si alloys results in decreasing density [4,25]. It should be noted that the differences between the data shown in Fig. 3 result not only from the differences in composition of alloys but to some extent also from the differences in methods used, as discussed in review [26].

Wettability study of the CGI-0/ Al_2O_3 couples [15] shows that in the course of the above-described

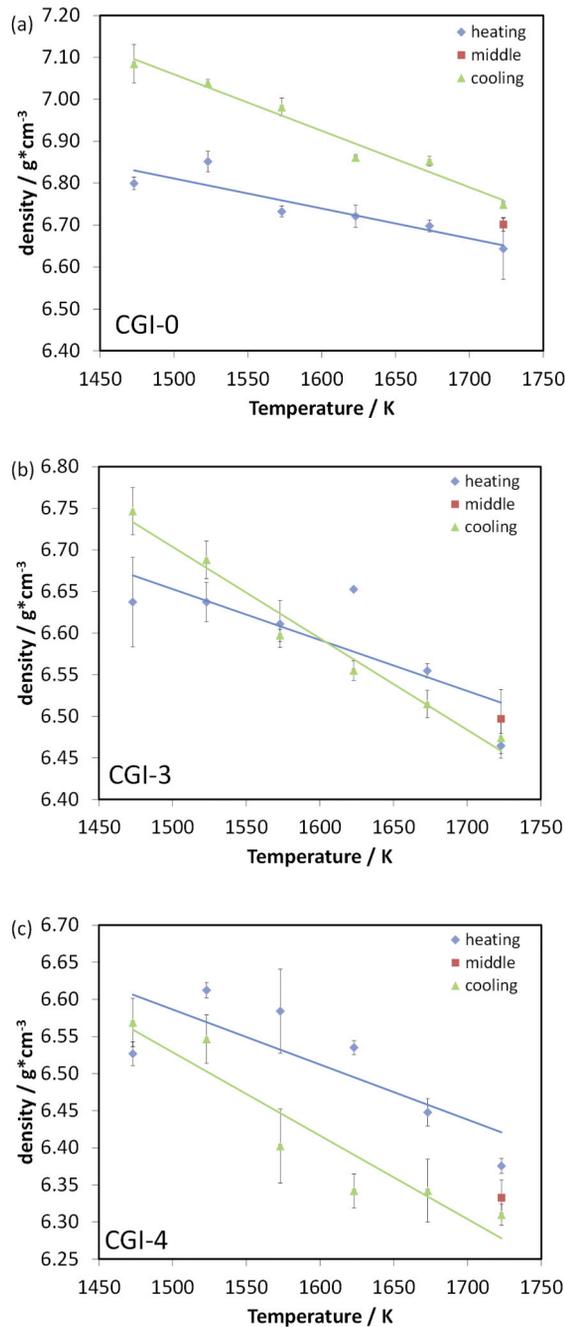


Figure 2. Density dependence on temperature for compacted graphite irons: (a) CGI-0, (b) CGI-3, (c) CGI-4

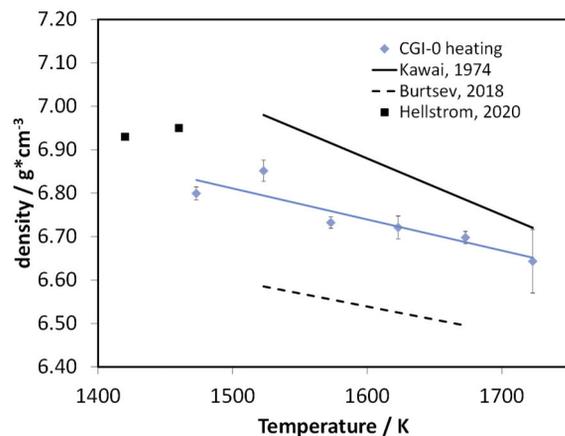


Figure 3. Density of CGI-0 compared with the literature density data for molten Fe-C-Si alloys (wt%): Fe-3C-2Si [4]; Fe-3.6C-2.8Si [5]; Fe-3.8C-1.74Si, Fe-3.64C-1.68Si [6]



Table 2. Summary of available literature data on density of molten cast irons. SD – sessile drop, LD – large drop, DIL – dilatometry

Ref.	Alloy [wt%]	d(T[K]) / [gcm ⁻³]	Method	T [K]	Substrate (container)	Atmosphere
This study	CGI-0	7.6892-0.0007T	SD	1473-1723	Al ₂ O ₃	Ar
This study	CGI-3	7.5706-0.0006T	SD	1473-1723	Al ₂ O ₃	Ar
This study	CGI-4	7.6995-0.0007T	SD	1473-1723	Al ₂ O ₃	Ar
[4]	Fe-3C-2Si	6.59-0.0013(T-1823)	SD	1773-1923	MgO	Ar (or H ₂)
[5]	Fe-3.6C-2.8Si-0.5P-0.3Mn-0.038S-0.002O	7.499-0.0006T	LD	1530-1660	–	Ar
[6]	Fe-3.8C-1.74Si-0.025P-0.53Mn-0.017S	6.93-0.0002121(T-1420)	DIL	1420-1549	Al ₂ O ₃	Ar
[6]	Fe-3.63C-1.68Si-0.023P-0.38Mn-0.013S	6.95-0.0002187(T-1440)	DIL	1440-1551	Al ₂ O ₃	Ar

experiment (exactly the same experimental conditions), the CGI-0 alloy does not wet the alumina substrate (the contact angle $\theta \ll 90^\circ$). Initially, once the CGI-0 drop is fully molten (at 1464 K), $\theta \sim 148^\circ$ while in the course of heating step, the contact angle decreases further to approximately 131° at 1723 K, but it does not significantly decrease any further during isothermal step and subsequent cooling. At the same time, the base of alloy drop widens indicating increasing area of the drop/substrate contact. Microstructural analysis of solidified sessile drop CGI-0/Al₂O₃ couple [15] revealed that two thin intermediate layers are formed at the alloy/substrate interface. The layer on the side of the drop is mostly composed of carbon, which seems to have nucleated on the alumina substrate during solidification of the drop, whereas the presence of carbon in the layer on the substrate side seems to be the result of the direct reaction between molten CGI-0 alloy and alumina [15]. Similar conclusions were drawn in another sessile drop tests performed in the same device and under the same testing conditions with compacted cast irons containing alloying additions [16]. In both cases, the microstructure of solidified drops differs from that of corresponding as-cast alloys, especially near the surface of the drop, where the graphite precipitates have a flake-like shape, characteristic for lamellar graphite iron (LGI). Although the chemical composition of solidified drops was not measured, the above observation suggests that the composition of CGI alloy was changing in the course of experiment, as molten CGI was in high temperature contact with alumina for nearly 50 min.

This change of composition might be the main reason why the thermophysical data recorded by container/substrate assisted methods on cooling do not reproduce the data recorded on heating. On the other hand, it is safe to assume that the data recorded on heating are representative for the alloy compositions listed in Table 1, rather than those

reported on cooling. These findings are different to those obtained with metals and alloys easily forming an oxide film on their surfaces. For example, for pure Sn, even though after mechanical removal, freshly formed oxide film has only nano-scale thickness, its further removal directly in the vacuum chamber of measurement device may cause an increase of surface tension of molten Sn up to 5-10%, depending on temperature [27]. Therefore, for Sn [20,27], Ag and Ag-Cu [28], and Sn-Ag-Cu [29], sessile drop measurements of thermophysical properties under vacuum were recommended in cooling regime (i.e., starting from overheated melt and next its step cooling), since it allows to produce metal drops less affected by native oxide film and thus, to get more reliable measurements.

Surface tension data determined for CGI-0, CGI-3 and CGI-4 alloys are graphically presented in Fig. 4. In contrast to the density, the values of surface tension are significantly scattered. One factor that accounted to this is the discussed earlier contamination of alloy due to chemical interaction of the melt with alumina substrate. In fact, it was already shown in the case of pure metals, including iron, that the sessile drop method, as a substrate-assisted technique, yields generally lower surface tension values than the contactless levitated drop method [30-36]. The volume of a sessile drop in this study was less than 0.1 cm³. Small drops tend to be close to circular in shape, the smaller the drop the more circular it is. This is noticeable for liquids of high surface tension such as Fe-based alloys. Hoofar and Neumann [37] showed that for a liquid of a known surface tension, uncertainty of surface tension measurements with algorithm [22] increases with the decreasing volume of a drop. Another factor that might be responsible for the scatter of surface tension data at particular temperatures is that, except for the isothermal part at 1723 K, drop images were recorded in this study on heating and cooling at a constant heating or cooling



rate, without isothermal steps that would allow the drop to attain thermal equilibrium.

The surface tension data of iron-based alloys found in literature (Table 3) are reported for alloys that differ not only regarding the content of carbon and silicon, but also other elements such as phosphorus, manganese, sulphur, and oxygen, the latter known to be surface active components in Fe-based alloys [4,5,7,25,30-36,38-40]. However, even for simple binary and ternary Fe-C-Si alloys, the

literature data are ambiguous (Fig. 4). The surface tension of iron alloyed with carbon and silicon was measured by few groups before. Kawai et al. [4] determined that, similar to Fe-C and Fe-Si alloys, the combined effect of increasing content of carbon and silicon leads to a decrease of surface tension. Lee and Morita [38], on the other hand, reported that the surface tension of Fe-4C (wt%) is actually higher than that of pure iron. Considering the temperature dependence, surface tension of all the alloys studied by Kawai et al. [4] generally decreases with increasing temperature over the entire considered temperature range. An opposite tendency was found by Burtsev et al. [5] and Holtzer and Retel [7], who carried out surface tension measurements on heating with 5 min long isothermal steps every 20-30 K and 50 K, respectively. Holtzer and Retel [7] observed two distinct temperature ranges: 1523 – 1773 K with surface tension increasing with temperature and 1773-1873 K with surface tension decreasing with temperature. They [7] attributed this change of slope to the chemical reaction $\langle \text{SiO}_2 \rangle + 2[\text{C}] = [\text{Si}] + 2\{\text{CO}\}$ leading to significant (~50 %) reduction in carbon content in molten cast iron drop. Burtsev et al. [5] investigated narrower temperature range, however, the authors did not mention the material used for the containers in the large drop tests. It should be noted that neither of the sources cited above examined the solidified samples and interfaces formed between molten alloys and ceramic substrates or containers used in the sessile drop and the large drop tests, respectively.

For the measurements done in this study, it should be emphasized that to produce compacted graphite irons, molten alloys were also modified by magnesium just directly before its casting, following the procedure reported in [14]. However, under high temperature conditions of sessile drop tests, the amount of residual magnesium in CGI is continuously changing due to two reasons, i.e., magnesium evaporation and its consumption for the reaction with alumina substrate. Sobczak et al. [16] observed that these two phenomena are responsible for the structural change of initially CGI sample since in the solidified drops, the structures of a surface layer as well as of that located close to the drop/substrate interface become typical for LGI, i.e., conventional grey cast iron untreated with Mg. These findings are in a good agreement with experimental study of Vashchenko and Rudoi [39] showing that during holding Mg-treated cast iron melt on ceramic substrate at 1673 K, the amount of Mg continuously decreases thus resulting in corresponding increase of surface tension of the melt with holding time. The above-mentioned circumstances explain also scattering experimental data and possible unusual temperature dependence of surface tension of molten

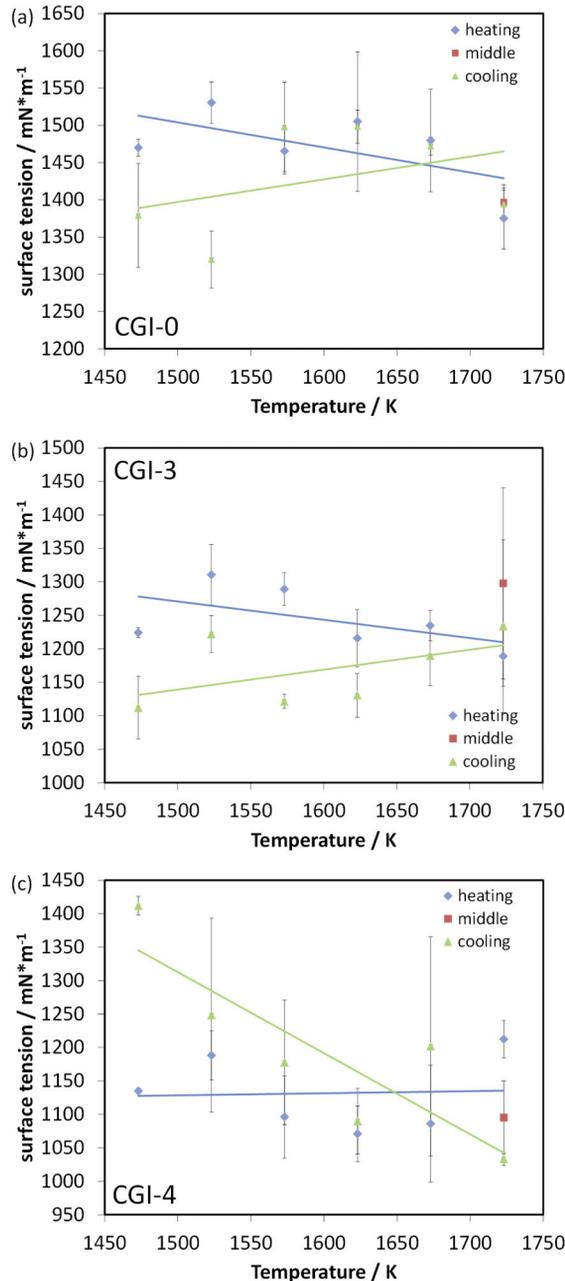


Figure 4. Surface tension dependence on temperature for compacted graphite irons: (a) CGI-0, (b) CGI-3, (c) CGI-4

CGI alloys and this fact should be taken into consideration in the selection of testing procedure for measurements of thermophysical properties of compacted graphite irons, especially by substrate/crucible assisted methods.

Our previous studies on interaction between different cast iron alloys and oxide-based substrates during the sessile drop tests [15,16] accompanied with classical contact heating procedure evidenced many methodological problems of testing such high-temperature systems that explains a large scattering in literature data. Based on this experience, there is no doubt that more work is needed to understand factors affecting surface tension measurements of cast irons at different stages of sessile drop tests. Most probably, for this purpose, it will be necessary to develop a particular method or procedure, considering our well-documented data on changes in the surface chemistry of solidified sessile drop couples (both of cast iron and oxide substrate) during testing accompanied with conventional contact heating procedure. It must be clearly said that surface tension measurements are performed when the selected alloys are completely molten while their later structural characterization and chemical analysis of “critical” near-surface regions and near-interface regions of the alloy drops are performed at room temperature after their high temperature interaction with the substrate. Thus, not only heating history but also cooling history might play an important role in the distribution of alloying elements and impurities in solidified drops. Considering this fact, structural changes and surface chemical analysis should be done in situ directly during the sessile drop testing, including solid and liquid states of cast iron samples. However, it is still impossible in any laboratory in the world. Therefore, for this stage of research, we would not like to speculate and make any solid conclusions on the relationships between surface tension and structure of solidified drops, because of the unknown kinetics of high temperature phenomena taking place in initially compacted graphite cast iron samples under applied

conditions used in our sessile drop tests (e.g. evaporation of residual Mg from the drop, reaction of residual Mg from the alloy with oxide substrate, changing chemical composition of the drop-surface region due to evaporation Mg and its consumption for the reaction with the substrate, specific heat transfer conditions during cooling, the formation of clatters in molten cast iron, etc.). Although we do not know quantitative relationships, we conclude that above mentioned phenomena affect surface tension values even during sessile drop measurements that explains scattering literature data as well as differences in our measurements using heating and cooling modes. This conclusion is of practical importance, particularly in proper selection of surface tension values in computer simulation of nucleation of graphite and solidification of cast iron alloys.

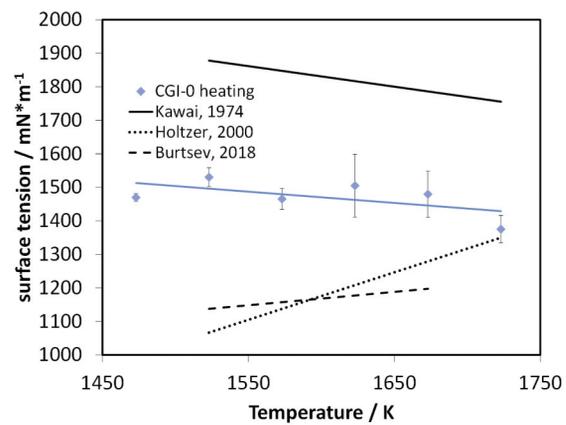


Figure 5. Surface tension of CGI-0 compared with the literature data for molten cast irons and Fe-C-Si alloys (wt%): Fe-3C-2Si [4]; Fe-3.6C-2.8Si [5]; Fe-3.81C-1.69Si [7]

4. Conclusions

For the first time, density and surface tension of molten compacted graphite irons were measured with

Table 3. Surface tension of liquid compacted graphite irons together with selected literature data. SD – sessile drop, LD – large drop

Ref.	Alloy [wt%]	$\sigma(T[K]) / [mN \cdot m^{-1}]$	Method	T [K]	Substrate	Atmosphere
This study	CGI-0	2007-0.3356T	SD	1473-1723	Al ₂ O ₃	Ar
This study	CGI-3	1679-0.2726T	SD	1473-1723	Al ₂ O ₃	Ar
This study	CGI-4	1081+0.0316T	SD	1473-1723	Al ₂ O ₃	Ar
[4]	Fe-3C-2Si	1694-0.614(T-1823)	SD	1773-1923	MgO	Ar or H ₂
[7]	Fe-3.81C-1.69Si-0.044P-0.034Mo-0.0157S-0.0063O-1.024Sc	-1092.6+1.4177T	SD	1523-1773	SiO ₂ (with binders)	He
[5]	Fe-3.6C-2.8Si-0.5P-0.3Mn-0.038S-0.002O	528.7+0.3997T	LD	1530-1660	–	Ar



the sessile drop method on polycrystalline alumina substrates under inert atmosphere and isothermal conditions in the temperature range of 1473 – 1723 K, both in heating and cooling regimes.

Density of all three CGI alloys measured on heating decreases with increasing temperature with similar slope. Density data determined on cooling do not overlap with the density determined on heating because of evaporation of residual magnesium from molten compacted graphite iron and chemical reaction taking place between the melt and alumina substrate. These high temperature phenomena contribute to essential methodological problems of reliable measurements of thermophysical properties of molten compacted graphite irons by substrate/container-assisted techniques since they are the key reason for ambiguous surface tension results. Nevertheless, as reaction between the drop and the substrate progresses with time, the surface tension measured on heating is considered more representative for the studied alloys.

Acknowledgments

This research was financed by the National Science Centre of Poland in the frame of OPUS program (grant No. 2015/17/B/ST8/03391). The authors thank G. Bruzda for technical assistance in the sessile drop tests.

Author contributions

N. Sobczak conceived the idea for this paper, conducted sessile drop tests, wrote the introduction part. P. Fima processed sessile drop images, wrote draft of experimental part and results. N. Sobczak and P. Fima surveyed the literature, wrote discussion part and conclusions, reviewed the manuscript.

Data availability

Raw sessile drop images are with N.S. and may be available to interested party upon written request, if such a request is found feasible.

References

- [1] J.J. Valencia, P.N. Quested, Thermophysical Properties. In: ASM Handbook, vol. 15: Casting, ASM Handbook Committee, 2008, p. 468-481.
- [2] D.M. Stefanescu, A History of Cast Iron. In: ASM Handbook, vol. 1A Cast Iron Science and Technology, ASM International, 2017, p. 3-8.
- [3] M. Holtzer, M. Górny, T. Daňko, Microstructure and Properties of Ductile Iron and Compacted Graphite Iron Castings. The Effects of Mold Sand/Metal Interface Phenomena. Springer Briefs in Materials, Springer, 2015, p. 27-42.
- [4] Y. Kawai, K. Mori, M. Kishimoto, K. Ishikawa, T. Shimada, Tetsu To Hagane, 60 (1974) 29-37.
- [5] V.T. Burtsev, S.N. Anuchkin, A.V. Samokhin, Nanotechnol. Russ., 13 (2018) 594–601.
- [6] K. Hellström, V.-L. Diaconu, A. Diószegi, China Foundry, 17 (2020) 127-136.
- [7] M. Holtzer, K. Retel, Can. Metall. Q., 39 (2000) 339-344.
- [8] T. Skaland, Ø. Grong, T. Grong, Metall. Mater. Trans. A, 24 (1993) 2321–2345.
- [9] D. Stefanescu, G. Alonso, D. Suarez, Metals-Basel, 10(2) (2020) 221.
- [10] G.Q. Shi, Z. Yang, J.P. Li, D. Tao, J.M. Ma, J. Mater. Res. Tech., 9(4) (2020) 8186-8196.
- [11] G. Alonso, P. Larrañaga, D.M. Stefanescu, R. Suarez, Inter. J. Metalcast., 14(4) (2020) 1162-1171.
- [12] D. Shi, D. Li, G. Gao, L. Wang, Kovove Mater. 46 (2008) 59–61.
- [13] R.F. Brooks, P.N. Quested, J. Mater. Sci. 40 (2005) 2233-22-38.
- [14] M. Homa, N. Sobczak, P. Turalska, G. Bruzda, M. Baciór, M. Warmuzek, A. Polkowska, Trans. Foundry Res. Inst., LVII (4) (2017) 345-350.
- [15] M. Baciór, N. Sobczak, M. Homa, P. Turalska, A. Kudyba, G. Bruzda, R. Nowak, A. Pytel, Trans. Foundry Res. Inst., LVII (4) (2017) 375-384.
- [16] N. Sobczak, M. Baciór, P. Turalska, G. Bruzda, M. Homa, J.J. Sobczak, Arch. Metall. Mater., 65 (2020) 1227-1238.
- [17] N. Sobczak, M. Singh, R. Asthana, Curr. Opin. Solid State Mater. Sci., 9 (2005) 241-253.
- [18] N. Sobczak, J. Sobczak, R. Asthana, R. Purgert, China Foundry, 7 (4) (2010) 425-437.
- [19] N. Sobczak, R. Nowak, W. Radziwill, J. Budzioch, A. Glenz, Mater. Sci. Eng., 495 (2008) 43-49.
- [20] P. Fima, R. Nowak, N. Sobczak, J. Mater. Sci., 45 (2010) 2009-2014.
- [21] M. Kucharski, P. Fima, Arch. Metall. Mater., 49 (2004) 565-573.
- [22] Y. Rotenberg, L. Boruvka, A.W. Neumann, J. Colloid Interface Sci., 93 (1983) 169-183.
- [23] K. Ogino, A. Nishiwaki, Y. Hosotani, J. Japan Inst. Metals, 48 (1984) 1004-1010.
- [24] J. Jimbo, A.W. Cramb, Metall. Mater. Trans. B, 24 (1993) 5-10.
- [25] C. Dumay, A.W. Cramb, Metall. Mater. Trans. B, 26 (1995) 173-175.
- [26] A.F. Crawley, Int. Metall. Rev., 19 (1974) 32-48.
- [27] R. Nowak, N. Sobczak, T. Lanata, E. Ricci, B. Korpała, Trans. Foundry Res. Inst., XLIX (4) (2009) 5-13. (in Polish)
- [28] P. Fima, N. Sobczak, Int. J. Thermophys., 31 (2010) 1165-1174.
- [29] P. Fima, Int. J. Mater. Res. 103(12) (2012) 1455–1461.
- [30] M.E. Fraser, W.K. Lu, A.E. Hamiele, R. Murarka, Metall. Trans. 2 (3) (1971) 817–823.
- [31] A. Kasama, A. McLean, W.A. Miller, Z. Morita, M.J. Ward, Can. Metall. Q., 22 (1) (1983) 9–17.
- [32] K. Nogi, K. Ogino, A. McLean, W.A. Miller, Metal. Mater. Trans. B, 17 (1986) 163-170.
- [33] B.J. Keene, Int. Mater. Rev., 33 (1) (1988) 1–37.
- [34] V. Brooks, I. Egry, S. Seetharaman, D.M. Grant, High Temp.-High Press., 33 (6) (2001) 631-637.



- [35] J. Brillo, I. Egry, J. Mater. Sci., 40 (9-10) (2005) 2213–2216.
- [36] S. Ozawa, S. Takahashi, H. Fukuyama, M. Watanabe, J. Phys. Conf. Ser., 327 (2011) 012020.
- [37] M. Hoorfar, A.W. Neumann, J. Adhes., 80 (2004) 727–743.
- [38] J. Lee, K. Morita, Steel Res., 73 (9) (2002) 369-372.
- [39] K.I. Vashchenko, A.P. Rudoi, Measurement of the surface tension of magnesium cast iron, in Surface Phenomena in Metallurgical Processes (A.I. Belyaev), Springer, Boston, MA. 1965, p. 196-202.
- [40] V. Novák, L. Řeháčková, P. Váňová, B. Smetana, K. Konečná, L. Drozdová, S. Rosypalová, J. Min. Metall. Sect. B-Metall., 56 (2) (2020) 143 – 151.

GUSTINA I POVRŠINSKI NAPON TEČNOG LIVENOG GVOŽĎA

P. Fima *, N. Sobczak

Institut za metalurgiju i nauku o materijalima, Poljska akademija nauka, Krakov, Poljska

Apstrakt

Kompjuterski potpomognut razvoj metalurških procesa sa učešćem tečnosti zahteva pouzdane osnovne podatke o tečnim materijalima, uključujući i termofizičke osobine kao što su gustina, površinski napon, i viskozitet. Liveno gvožđe pripada grupi Fe-C legura koje imaju praktičnu vrednost zbog svojih dobrih tehnoloških i upotrebnih osobina, pa ipak, u literaturi ima malo eksperimentalnih termofizičkih podataka o livenom gvožđu. U ovom radu merena je gustina i površinski napon tri vrste legura kompaktnog grafitnog livenog gvožđa uz pomoć metoda viseće kapi u kontaktnom režimu zagrevanja pri temperaturnom opsegu od 1473 – 1723 K sa polikristalnom glinicom kao supstratom. Slike profila kapi zabeležene su kako tokom režima zagrevanja tako i tokom režima hlađenja koji su usledili. Pri temperaturi od 1473 K vrednosti gustine ispitivanih kompaktnih grafitnih gvožđa su između 6.66 i 6.69 g·cm⁻³, dok su vrednosti površinskog napona između 1130 i 1510 mN·m⁻¹. Gustina opada kako temperatura raste, dok je zavisnost površinskog napona od temperature manje očita. Dobijeni rezultati upoređeni su sa postojećim podacima u literaturi, i analizirani uzimajući u obzir hemijske interakcije tečnog livenog gvožđa sa supstratom.

Ključne reči: Kompaktno grafitno gvožđe; Gustina; Površinski napon; Metod viseće kapi

