Thin Wall Cast Iron: Phase II

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Final Report submitted by
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1 Executive Summary

The development of thin-wall technology allows the designers of energy consuming equipment to select the most appropriate material based on cost/material properties considerations, and not solely on density. The technology developed in this research project will permit the designers working for the automotive industry to make a better informed choice between competing materials and thin wall cast iron, thus decreasing the overall cost of the automobile.

The Thin Wall Iron Casting Phase I project has developed the fundamental processing knowledge for the production of thin wall (2.5-4mm) iron castings. The results showed that thin-wall ductile (DI) and compacted graphite (CGI) iron castings free from carbides, inverse chill and microporosity, having excellent mechanical properties, could be produced in iron foundries without major capital investments. The statistical analysis of the data from ferritic and pearlitic sound ductile iron machined plates demonstrated that the general process-microstructure-mechanical properties known for regular-wall DI apply also for thin-wall DI. The use of cooling curve analysis proved to be a reliable tool for predicting graphite shape.

The emphasis of the Thin Wall Iron Casting Phase II project was on developing the technology required for implementation of the fundamental processing knowledge gained in Phase I of the project. Some of the major technical accomplishments are summarized in the following paragraphs.

In Phase I of this research, the static mechanical properties of horizontal-plates thin ductile iron castings (1.5 to 6 mm) were measured. It was found that the properties of these castings have the potential of being equivalent or superior to current ASTM specifications for regular size (12.7 mm) ductile iron castings. However, the data were widely scattered, with many plates exhibiting substandard properties.

Consequently, in this research the pattern was redesigned and sound vertical-plate castings (2.5 to 6 mm) were produced.[1] The cooling rates of these plates ranged from 4.6 to 12 ºC/s. Copper additions were used to cover a microstructure ranging from 80 to 20% ferrite. To obtain a predominantly pearlitic matrix, copper additions in excess of 0.2% were required. The results of the testing of the as-cast and fully machined tensile samples produced from the thin plates demonstrated that mechanical properties of fully machined thin wall (2.5 to 6 mm thick, 4.6 to 12 ^{o}C/s cooling rate) ductile iron plates are equivalent or superior to regular section (12.7 mm) ductile iron. The reasons for the lower values previously reported by other investigators are solidification anomalies and/or surface roughness. Indeed, the surface quality of the test plates greatly influenced the level of mechanical properties.

Preliminary measurements on the influence of average surface roughness indicated that there is a roughness threshold, above which a noticeable decrease in both strength and elongation is recorded. It was also demonstrated that surface roughness is greatly influenced by the metallostatic pressure and the pouring temperature of the casting. Higher metallostatic pressure and pouring temperature result in greater surface roughness.

The influence of cooling rate on the mechanical properties of ferritic iron was negligible. However, lower tensile strengths were recorded as the cooling rate increased for pearlitic ductile iron plates, because of the higher ferrite content.

Statistical analysis was performed to correlate the mechanical properties of thin wall ductile iron to the processing variables and the microstructure. To establish the base line for regular section ductile iron, several ASTM U-block mechanical testing specimens were also produced and tested. Good correlation was found between cooling rate and nodule count for both ferritic and

[1] L.P. Dix, R. Ruxanda, J. Torrance, M. Fukumoto and D.M. Stefanescu, “Static Mechanical Properties of Ferritic and Pearlitic Lightweight Ductile Iron Castings,” Trans. AFS, **111** (2003) 1149-1164

pearlitic irons, as well as between the copper and ferrite content and the mechanical properties. It was concluded that the high nodule count associated with the increased cooling rates of thin wall castings is a major factor in matrix evolution. Indeed, somehow surprisingly, it was found that because of the high nodule count produced by the rapid cooling rate, the ferrite content was higher in the thinner plates.

The surface quality of the samples affected their mechanical properties. Typically, as-cast samples exhibited lower properties than their fully machined counterparts did. The ferritic samples were more severely affected by surface quality than the pearlitic samples.

To fully document the role of surface quality, the as-cast surfaces were analyzed and quantified with a profilometer. It was found that the surface roughness of the vertical-plate castings depends on the metallostatic pressure and the pouring temperature. Higher pouring temperatures and metallostatic pressures produced rougher surface finish. The properties decreased significantly above a certain critical roughness.

Extensive experimental work was conducted to further investigate the influence of surface roughness on the static mechanical properties of thin-wall ductile iron castings.[2] The test casting was a three-plate vertical casting with thickness of 6, 2.5, and 3.5 mm (from bottom to top). The charge materials included 20% low manganese steel scrap, 40% Sorel pig iron and 40% ductile iron returns. The carbon equivalent ranged from 4.57-4.64%. Under these experimental conditions all the vertical plates were free of carbides, had a ferritic matrix, and exhibited no internal defects.

The use of a combination of surface treatments produced surface roughness measurements as low as 3.1 μm. However, roughness lower than 4 μm was consistently obtain through the use of finer sand (*GFN91*) and a graphitic water-based coating. Coating was very efficient even on the coarse sand (*GFN53*). The roughness of plates cast in coarse grain sand was improved by up to 47% by shot peening, and by an average of 38% by coating the sand with a graphitic water-based coat.

When fine grain coated sand was used, peening yielded no further improvement, but rather a slight increase in roughness (1 to 6%). Nevertheless, 5 minutes of shot peening reduced the roughness of all uncoated plates to about 4 μm.

The improvement of surface quality achieved through mold coating or/and shot peening resulted in an average increase of as-cast (machined only on two surfaces) UTS of 7 ksi as compared with previously published data by Dix *et al*. (2003).

It was demonstrated that the geometry of the machined specimen edge on the flat rectangular tensile specimen significantly affected the mechanical properties. With proper preparation (chamfering), stress raisers at the sharp edged corners of the specimens were reduced and resulted in increased strength and elongation.

The use of a high graphite water-based mold coating was the most efficient surface treatment, producing the lower surface roughness. However, the graphitic coating produced a pearlitic rim on the surface of the coated castings. The mechanism for the rim formation was assumed to be carbon diffusion from the coating into the outer layer of the casting. The occurrence of the pearlitic rim increased the UTS and slightly lowered elongation.

Melt preconditioning experiments were conducted to improve microstructure control.[3] It was found that preconditioning as used in this work is effective only at cooling rates lower than 19 °C/s. Indeed, for any given pouring temperature, the 6 mm plate (9.2 °C/s) and the 4 mm plate

[2] J.W. Torrance and D.M. Stefanescu, "An Investigation on the Effect of Surface Roughness on the Static Mechanical Properties of Thin-Wall Ductile Iron Castings," Trans. AFS, **112** (2004)

[3] F.R. Juretzko, L.P. Dix, Roxana Ruxanda and D.M. Stefanescu, "Precondition of Ductile Iron Melts for Light Weight Castings - Effect on Mechanical Properties and Microstructure," Trans. AFS, **112** (2004)

(12 °C/s) exhibit 32%, respectively 11% higher nodule count with preconditioning than without, while for the 2 mm plates (19.8 °C/s), a nodule count reduction of 10% was found. This is in line with previous research that demonstrated that the effect of preconditioning decreases as the cooling rate increases.

It was apparent that preconditioning produces a more uniform size distribution of the graphite particles at any cooling rate. From the statistical analysis it was concluded that a better fit of the experimental data with the normal distribution model was obtained for the preconditioned samples than for the not preconditioned ones. This effect was more pronounced in the 6 mm plates than in the 2 mm plates. Thus, the beneficial effect of preconditioning on the melt is achieved by a better distribution of the graphite size, although the nucleation potential is not necessarily increased through preconditioning.

During this research we have demonstrated that microshrinkage can be easily avoided in thin wall ductile iron (DI) with appropriate feeding either from a riser or from adjacent sections.[4] The experimental results indicated that, with proper feeding, it is possible to cast sound horizontal plates with dimensions of 2x60x100 mm. It was also found that microshrinkage tends to decrease with increasing cooling rate for independent horizontal plates. However it was not possible to obtain good correlation between microshrinkage and other processing variables because of feeding difficulties experienced by the horizontal plates.

These results prompted additional effort to investigate the influence of process variables on microshrinkage formation in independent plates which are filled at an angle of 15° from horizontal.[5] These plates fill in a controlled manner without turbulence. The new design was evaluated by comparing modeling results obtained with NovaCast & NovaFlow ® software with images obtained through high speed video. The experimental results demonstrate that in thin DI plates that solidify with no feeding from a riser or an adjacent section, microshrinkage decreases as cooling rate increases. In line with this, a higher pouring temperature promotes lower microshrinkage, although the data scatter is rather significant. When compared with the findings of our previous work (Woolley *et al.*, 2004), it is reasonable to conclude that by controlling the mold filling, microshrinkage data scatter is dramatically reduced as a much higher correlation between microshrinkage and cooling rate is observed. The reduction of the thermal conductivity of the mold through the addition of a low-density alumina-silicate ceramic (ASC) has been demonstrated to improve results consistency because of more uniform solidification pattern.

Over the past decade, computer simulation of mold filling and solidification has significantly impacted the casting industry by reducing the scrap rate and improving casting soundness. While simulations are driven by laws of physics, the large number of assumptions used in the models requires careful model validation against experiments. In the past such work has been done with model substances, as well as X-ray film recordings. However, actual mold filling occurs much faster than can be captured in detail with conventional film or video recording equipment. Using a much higher frame rate available through a high speed video camera we have recorded the filling of resin-bonded molds with cast iron in real-time.[6] Details of the dynamic filling are compared with simulation results. In addition the influence of filters on mold filling is assessed. The possibility to use this technique to properly select the filter coefficient for computer simulations is also discussed.

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[4] J.W. Woolley, R. Ruxanda, M. Liliac, M. Fukumoto, D.M. Stefanescu, and C. Heisser, "Factors Affecting Microshrinkage Formation in Thin Wall Ductile Iron," Trans. AFS, **112** (2004)

[5] J.W. Woolley and D.M. Stefanescu, "Microshrinkage Propensity in Thin Wall Ductile Iron Castings", Trans. AFS, **113** (2005) paper 05-094

[6] F.R. Juretzko, D.M. Stefanescu, "Comparison of mold filling simulation with high speed video recording of real-time mold filling" Trans. AFS, **113** (2005) paper 05-174

The delayed in-mold (DIM) process is claimed to be a good alternative to the classic in-mold process for accurate control of the magnesium residual in ductile and compacted graphite (CG) iron. The DIM process requires a reaction chamber preceded by a mixing basin. The role of the mixing basin is to ensure complete mixing of the liquid iron after dissolution of the magnesium alloy. Its volume is designed such as to be equal to or exceed the volume of the casting including runner and riser. Literature data indicate that CG iron can be obtained by sulfur additions made after the magnesium treatment. The optimum Mg/S ratio was reported to be in the range of 0.5 and 2 for regular section size castings.

We explored the possibility of producing CG in thin castings by tight control of the magnesium and sulfur level.[7] Test castings including plates with thickness of 3, 4.5 and 6 mm were used. The plates were separated by cylindrical risers and poured in vertical molds. Experiments were designed to find the optimum magnesium/sulfur ratio (Mg/S) required to obtain consistent compacted graphite structure with the DIM process. The Mg/S ratio for thin wall castings was maintained in the range of 0.5 to 1.5. The correlation between the microstructure and the tensile mechanical properties was also investigated.

The experiments demonstrated that even with the DIM process the control of *Mg* and *S* residuals is difficult at best. Nodularity varied between 25 and 70 %, with the higher nodularity being associated with the thinner plates. Thus, it was not possible to consistently produce CG iron. However, the properties of these low-nodularity DI were surprisingly high. Elongations ranged from 12 to 20%, while the ultimate tensile strength ranged from 62 to 71 ksi. In general the mechanical properties exceeded the ASTM standards for both CG and ductile iron. The mechanical properties were fairly consistent over the whole range of Mg/S ratio and thickness investigated.

The complete results of this research have been summarized in seven research papers published in the Transactions of the American Foundry Society. These papers have been referenced as foot notes in this Executive Summary and are attached to this report.

In summary, the results of this research demonstrated that it is possible to produce sound DI casting as thin as 2.5 mm without capital investments. The static mechanical properties of the DI cast in thin plates are superior or equivalent to those of regular size (25 mm) castings. However, mechanical properties are strongly influenced by the surface quality of the castings. Means of improving surface quality were addressed in this research. The application of this technology will result in considerable energy savings.

[7] D.M. Stefanescu, R.C. Rao, J.W. Woolley, F.R. Juretzko and J.W. Torrance, "Production of Thin Wall Low-Nodularity Ductile Iron through the Delayed In-Mold Process" Trans. AFS, **113** (2005) paper 05-110

2 Comparison of the Actual Accomplishments with the Goals and Objectives of the Project.

The proposal for Phase II of the Thin Wall Cast Iron lists six major tasks, as shown in Table 1. These six tasks were to be performed at The University of Alabama. These tasks will be presented in more detail in the following paragraphs.

Table 1 List of identified main tasks

Task	Description	Note
1	Evaluation of the influence of process variables on microporosity and inverse chill.	Dependent variables are microporosity and inverse chill, while independent variables are 1 a - metal chemistry, 1 b - temperature gradient, 1 c - cooling rate, and 1 d - metal treatment.
2	Establishment of feeding distance rules	This includes the evaluation of certain geometries and chemistries to promote inverse chill.
3	Establishment of thermally-based criteria functions for microporosity and inverse chill.	Criteria to be incorporated into solidification modeling software.
4	Correlation of mechanical properties with local cooling rates and microstructure.	Establish data base to aid in the development of solidification software, Includes work on delayed in-mold (CGI)
5	Investigation of the effects of surface roughness on mechanical properties.	For thin wall cast iron, the surface condition plays a more important role for the overall properties. The mechanical test performed is the static tensile test, yielding UTS, YS, and elongation data.
6	Development of design guidelines for sound thin wall iron castings.	Guidelines are targeted to yield thin wall castings with reproducible properties.

2.1 Comparison of main tasks with accomplishments

Based on these tasks, Table 2 contrasts the actual work performed with the outlined tasks. It is seen that the performance of the research group not only completed the tasks but exceeded the initial scope to answer questions of scientific and technical relevance, which were identified during the research effort.

Table 2 Comparison of proposed and actual work.

Task	Title	
1 a	Evaluation of the influence of process variables on microporosity and inverse chill - **metal chemistry**	Task 1 has been completed. See *Wooley et al*. (2004) and *Wooley and Stefanescu* (2005) for details. As part of the *metal treatment* investigation, a detailed study was undertaken to investigate the potential of pre-conditioning of the melt to achieve better mechanical properties and a potential remedy to Monday-morning iron. This has been incorporated into the task outline as Task 7.
1 b	Evaluation of the influence of process variables on microporosity and inverse chill - **temperature gradient**	
1.c	Evaluation of the influence of process variables on microporosity and inverse chill - **cooling rate**	
1 d	Evaluation of the influence of process variables on microporosity and inverse chill - **metal treatment**	
2	Establishment of feeding distance rules	Task completed. See *Wooley et al*. *(2004)*
3	Establishment of thermally-based criteria functions for microporosity and inverse chill.	Task completed. See *Wooley et al*. *(2004)*
4	Correlation of mechanical properties with local cooling rates and microstructure.	Task completed. See *Dix et al. (2003)* for details.
5	Investigation of the effects of surface roughness on mechanical properties.	Task completed. See *Torrance and Stefanescu (2004)* for details.
6	Development of design guidelines for sound thin wall iron castings.	Task completed on the conversion of a connector casting from aluminum to thin wall DI. See Monthly Report December 03.
7	Effect of preconditioning on Thin Wall Cast Iron	Task completed. See *Juretzko et al. (2004)* for details

2.2 Comparison of secondary tasks

In addition to these six main tasks, further action items were identified in the proposal and are listed and presented in the subsequent paragraphs.

2.2.1 Gathering data on production lines in commercial foundry lines (p.3)

No information.

2.2.2 On-site measurements of temperature gradients in representative castings such as engine blocks (p.7)

No information of measurements.

Did proof of concept conversion casting of thick wall aluminum connector casting to thin wall DI casting on part from Cummins.

2.2.3 Evaluation of mechanical properties in sponsors laboratories (p.7)

No information.

2.2.4 Solicitation of final input parameters from participating foundries (p.11)

No information.

2.2.5 Feeding distance rules will be evaluated by mold filling observed by use of aerogel material (p.11)

The initial use of an aerogel mold was abandoned because of financial and availability constrains of the aerogel mold material. Instead, a number of molds were equipped with quartz windows at strategic locations and the mold filling was filmed with a rented high-speed video camera. Molds equipped with these quartz windows include

a) the standard TWIG vertically parted mold with unequal plate thickness. Results used in the evaluation of filter element implementation in mold filling simulations.
b) the delayed in-mold casting for CGI. Observations explained the variation of treatment success in these molds.
c) the horizontally parted TWIG mold with independent plates. Results used for feeding distance rules, and confirmed the necessity to redesign the pattern with inclined plates.
d) the angled TWIG mold with independent plates. Observations confirmed improved filling and thus the production of sound plates.
e) the proof-of-concept conversion of the Cummins connector casting. Recordings revealed discrepancy between the more splashing simulated filling and the quiescent filling of the actual casting.

2.2.6 Validation of criteria functions by participating foundries (p.11)

No information.

2.2.7 Collection of cooling rates of industrial interest on-site at participating foundries (p.12)

No information.

2.2.8 Generate tensile test data including (p.12)

UTS, YS, Elongation, Engineering stress strain diagram

2.2.9 Commercialization of the results by presentations to designers, by data sheets and targeted design clinics (p.14)

No information.

3 Summary of Project Activities

See attached papers.

4 Products Developed Under the Award and Technology Transfer Activities

4.1 Publications (list journal name, volume, issue), conference papers, or other public releases of results

F.R. Juretzko, D.M. Stefanescu, "Comparison of mold filling simulation with high speed video recording of real-time mold filling" Trans. AFS, **113** (2005) paper 05-174

D.M. Stefanescu, R.C. Rao, J.W. Woolley, F.R. Juretzko and J.W. Torrance, "Production of Thin Wall Low-Nodularity Ductile Iron through the Delayed In-Mold Process" Trans. AFS, **113** (2005) paper 05-110

J.W. Woolley and D.M. Stefanescu, "Microshrinkage Propensity in Thin Wall Ductile Iron Castings", Trans. AFS, **113** (2005) paper 05-094

D.M. Stefanescu, J. Torrance and L.P. Dix, "Factors Affecting the Mechanical Properties of Lightweight Ductile Iron Castings", The 66th World Foundry Congress, Istanbul, Foundrymen's Assoc. of Turkey (2004) 1003-1016

F.R. Juretzko, L.P. Dix, Roxana Ruxanda and D.M. Stefanescu, "Precondition of Ductile Iron Melts for Light Weight Castings - Effect on Mechanical Properties and Microstructure," Trans. AFS, **112** (2004)

J.W. Torrance and D.M. Stefanescu, "An Investigation on the Effect of Surface Roughness on the Static Mechanical Properties of Thin-Wall Ductile Iron Castings," Trans. AFS, **112** (2004)

J.W. Woolley, R. Ruxanda, M. Liliac, M. Fukumoto, D.M. Stefanescu, and C. Heisser, "Factors Affecting Microshrinkage Formation in Thin Wall Ductile Iron," Trans. AFS, **112** (2004)

L.P. Dix, R. Ruxanda, J. Torrance, M. Fukumoto and D.M. Stefanescu, "Static Mechanical Properties of Ferritic and Pearlitic Lightweight Ductile Iron Castings," Trans. AFS, **111** (2003) 1149-1164

4.2 Networks or collaborations fostered

Lodge Manufacturing was one of the industrial consortium members of this research effort. In their effort to reduce the wall thickness of their casting products, the Solidification Laboratory did support a number of test castings in the McFarabee Casting Laboratory with resin bonded sand, artificial sand with lower thermal conductivity and exploratory work using the delayed in-mold process with actual production patterns. As a result of this research, Lodge Manufacturing does now incorporate production methods, developed during Phase 2, to produce carbide free castings with a wall thickness of 0.08".

4.3 Technologies/Techniques

Delayed in-mold, in use at Lodge manufacturing.

4.4 Other products, such as data or databases, physical collections, audio or video, software or netware, models, educational aid or curricula, instruments or equipment.

During the performance period of this research other products have been developed which need to be listed under this heading. These are

1. Incorporation of thermo-physical data set for the artificial molding sand (Exactherm[8]) to be used in the mold filling and solidification software NovaCast. These data allow for the

[8] Product of Ashland Chemical Company.

simulation to be run with the proper material parameters and thus allow close comparison of the simulation results with the experimental evidence.

2. The high-speed video recordings have been presented in previous paragraphs, but their value for educational purposes cannot be understated. For one the comparison of direct visual observation to simulation results emphasized the value of computer simulation to students and other educators. In addition, the comparison of horizontal versus inclined mold cavity filling clearly demonstrates proper casting design principals with much more impact than any schematic.

4.5 Educational Impact of this research effort

The final report of this project would not be complete without assessing the impact this research had on the academic and professional lives of the participating students, as summarized in Table 3.

Table 3 Contributing students and researches of the Solidification Laboratory at The University of Alabama

Name	Status / Academic Product	Area of Contribution	Current Employment (2005)
Lucas Dix	Student / M.S.:	Mechanical properties, melt chemistry	American Cast Iron Pipe Co.
John Torrance	Student / M.S.:	Surface roughness	Torrance Casting
Masami Fukumoto	Visiting Scholar	Feeding Distance	Nissan
Roxana Ruxanda	Post-Doctoral Research Fellow	Metallography	Copeland Inc.
Marian Liliac	Post-Doctoral Research Fellow	Simulation, criteria function, feeding distance	Cummins Inc.
Jonathan Woolley	Current Master Student	Inverse Chill, criteria function, microporosity measurements	The University of Alabama
Frank R. Juretzko	Assistant Research Engineer	Precondition study, high speed video recording	The University of Alabama
Sombun Charaoenvilaisiri	Student / Ph.D.: Compacted Graphite Cast Iron	CGI mold design, testing and evaluation	Thailand University in Bangkok