PROGRAM OBJECTIVE(S)

The project objective is to determine the effects and allowable amounts of common residual alloying elements in solid solution strengthened ferritic ductile iron (SSFDI). SSFDI is ductile iron that contains significantly more silicon than conventional ductile iron grades (~4 wt.% Si total). Higher silicon levels fundamentally shift both the equilibrium phase stability and transformation kinetics. This alters the maximum allowable pearlite promoters that can mixed with these alloys during foundry operation. Determining the effects of pearlite promoting elements in SSFDI will provide commercial ductile iron foundries more confidence when utilizing their melting facilities to produce both conventional ductile iron and SSFDI without suffering unnecessary down time and material waste. The residual elements that will be studied include manganese, copper, and phosphorus. Effects of interest include their influence on the stability of pearlite and other phases under different cooling conditions, promotion of additional solid solution strengthening, and effects on mechanical properties.

COSTS

<table>
<thead>
<tr>
<th>Project expenditures</th>
<th>Cost</th>
<th>Secured or Requested Funding</th>
</tr>
</thead>
<tbody>
<tr>
<td>Student stipend and fringes</td>
<td>$27,228</td>
<td>$17,500 (Gundlach AFS/DIS grain size project)</td>
</tr>
<tr>
<td>Student tuition and fees</td>
<td>$24,800</td>
<td>$4,500 (requested from Michigan Tech)</td>
</tr>
<tr>
<td>Supplies and services</td>
<td>$11,295</td>
<td></td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>$63,323</strong></td>
<td><strong>$22,000</strong></td>
</tr>
</tbody>
</table>

The total cost per Michigan Tech budgeting is $63,232. Our collaboration with Rick Gundach on the AFS/DIS grain size strengthening project will be used to support Julia. Also, we have requested (but not yet secured) some tuition support from Michigan Tech. This leaves $41k to complete the proposed MS work. We are seeking some funds (about $5k each) from several industrial sponsors to augment any direct project funding from AFS and DIS. If other partners contribute, funding in the range of $20-30k from DIS would be appreciated. Finally, Julia is applying for FEF scholarships to support her MS work.
Student stipend and fringes are for one year of support (January to December 2018) and are at standard university rates for an MS student. Tuition and fees are also for one year of support (January to December 2018) and are at standard university rates for an MS student in the Materials Science and Engineering Department.

Supplies and Services include materials for the research ($4,288), such as alloys, gases, crucibles, minor instrumentation, safety supplies, and reference materials; and equipment use fees ($7,007) for the foundry, mechanical testing, and characterization facilities.

All costs are calculated using the reduced overhead rate of 22.5% for AFS/DIS projects. No overhead is charged on tuition, per Michigan Tech’s approved F&A cost rate agreement.

**TIME TO COMPLETION:** Total Project 16 months; Funding Period: 12 months

Project Start: September 2017 (finish BS in December 2017; begin MS in January 2018)

Project Finish: December 2018

**ECONOMIC JUSTIFICATION AND PRACTICAL APPLICATION**

In SSFDI, pearlite fractions above 5% are unacceptable and it is known that Mn levels must be below 0.50 wt.% to lower the risk of exceeding the pearlite threshold (DIN EN 1563). Unfortunately, the combined levels of other pearlite promoting elements such as Cu, Ni, Cr, and Sn are not specified. The pearlite promoting elements previously listed are commonly found in more conventional ductile iron grades and therefore they may be incorporated into SSFDI heats from the heels of previous melts.

Due to uncertainty about the influence of pearlite formers, many foundries may choose to pig the heels of conventional iron grades before producing SSFDI compositions. This cost in raw materials, energy, and time may impede SSFDI implementation. If studies are conducted on the effects of pearlite promoting elements, foundries may more efficiently utilize their melting resources when casting SSFDI and realize manufacturing cost savings. Information on the pearlite promotion potency in SSFDI could also aid in lowering costs associated with charge make-up. Lower cost additions of scrap steel and returns could be used instead of higher cost virgin materials as long as the maximum thresholds for pearlite promoters are avoided.

Performing this research at Michigan Tech would be beneficial because Michigan Tech has a pilot-scale foundry capable of producing 300 lb ductile iron heats via induction melting. This is very cost efficient compared to production-scale trials. With proper process control, industrially scaleable results may be obtained. Michigan Tech will also utilize a variety of characterization techniques such as mechanical testing, and optical and electron microscopy.
POSSIBILITY OF SUCCESS

The study on the effect of pearlite promoters is highly probable (~95%) to achieve useful information that currently does not exist in literature and which will be useful to industrial foundries. Potential risk factors involve issues with controlling residual element chemistry to the levels that will allow resolution of their effects on pearlite formation.

HISTORY AND THEORY

Traditional ductile iron has a mixed pearlite and ferrite matrix surrounding the nodules and is strengthened based on the relative amounts of each microconstituent. Elements, other than C and Si, intentionally added in traditional ductile iron are magnesium, copper, manganese, nickel, tin, molybdenum, antimony, and rare earth elements. Elements generally seen as contaminants are sulfur, phosphorus, and some tramp elements from alloyed scrap steel used in the melt. Carbon forms the graphite nodules and the cementite in the pearlite. Silicon increases the ability of graphite to form by increasing the difference in temperature between the metastable and stable eutectic and also acts as a solution strengthener for the ferrite in the matrix. Magnesium and rare earths help to scavenge the sulfur and oxygen allowing the graphite to grow as spheres.

Additionally rare earth elements and antimony are used to control the graphite morphology. Copper, tin, molybdenum, antimony, and manganese act as pearlite promoters in that they increase the volume fraction of pearlite in the matrix. Nickel was originally added as part of the magnesium treatment but also provides solid solution strengthening in the ferrite [1]. Manganese behaves as a mild pearlite promoter, but also helps tie up sulfur, which will promote spiky graphite in high concentrations. Phosphorus in concentrations as low as 0.05 wt% forms particles of brittle phosphide, and forms a brittle phosphide network above 0.4 wt%, these phosphides are detrimental to the mechanical properties of the ductile iron [2]. Tramp elements from steel such as chromium and vanadium are carbide formers which can enhance wear resistance, but also embrittle the material and reduce machinability.

In the microstructure of traditional ductile iron the pearlite to ferrite ratio strongly impacts mechanical properties. A difficulty with the mixed pearlite and ferrite ductile iron is that the amount of pearlite is influenced not only by the alloying additions and the overall chemistry but is also strongly tied to the section size. Brockus in his paper on the “Effect of Section Size on Producing Ductile Iron Castings” illustrates this strong effect as the amount of pearlite in the matrix is plotted versus the section thickness (Fig. 1) [3]. The pearlite was about 10% in the 24 mm section and more than 80% in the 4 mm section.
One of the main differences between the solid solution strengthened ferritic ductile iron and the traditional pearlite-ferrite irons is that the hardness of the SSFDI is more uniform. Due to the difference in hardness between the pearlite and the ferrite in the traditional ductile iron it has localized hard and softer areas because of the changes in cooling rate at different locations in the part, as well as within the same run of castings. This is reflected in the international standard in which there is a single grade of solid solution strengthened ferritic ductile iron of 500-10. The specified hardness range for the solid solution ferritic grade is from 185-215 Brinell [4]. The range for the 500-07 pearlite-ferrite iron is from 170-230 Brinell, this range is twice as large as that of the ferritic grade [4].

The mechanical properties of these solid solution strengthened ferritic ductile irons have a range of between 250-470 MPa for the yield strength and between 400-600 MPa for the ultimate yield strength. The yield and ultimate tensile strength for the solid solution ferritic ductile irons increases as the amount of silicon increases up to about 4.3 percent, after which they start decreasing due to the embrittlement of the ferrite [5]. For a given tensile strength, the elongation of a solid solution ferritic ductile iron (up to 4.3 wt. % Si) is significantly higher than a pearlite-ferrite iron. The ratio of the yield to tensile properties of the solid solution ferritic iron is greater than that of the traditional mixed pearlite ferrite iron, with values of about 0.65 compared to 0.55 [5].

In terms of microstructure, the high levels of silicon reduces the tendency of carbide formation including the cementite found in pearlite resulting in a nearly fully ferritic matrix in the absence of strong pearlite promoters [5]. As the silicon content increases the nodule density increases as well because the silicon is a strong graphite promoter [5]. Some alloying additions other than silicon that have been examined for use in the solid solution ferritic ductile irons include cobalt, and nickel. The current European standard for 600-10 ductile iron requires a silicon amount of about 4.3 wt.% but the mechanical properties of the silicon strengthened irons decrease if more than about 4.4 wt.% silicon is added [1]. It was found that cobalt additions could stabilize solid
solution strengthened ferrite without the detrimental effects that occur with higher silicon levels [1]. Cobalt is a good candidates because the atomic radius is 135 pm compared to the 140 pm of iron. The effects of cobalt on traditional grades of iron are not as well known likely due to its high cost; cobalt is said to both increase and decrease the nodularity while it increases nodule density and reduces nodule size. However, cobalt increases the brittle transition temperature and decreases impact toughness, which is the opposite of nickel [1]. The addition of up to 4 wt.% cobalt maintains ferrite and increased the nodularity [1]. The effect on mechanical properties of the cobalt was not reported, but the microstructural results are promising [1]. Because the cost of cobalt is very high, these large amounts of alloying additions would not be practical for use in mass production in a commercial foundry. However, cobalt is one of only a few ferrite promoting alloying additions and could be useful in small amounts of to negate the effects of the pearlite promoting elements and/or to provide additional solid solution strengthening for the 600-10 iron without overshooting the silicon level.

Traditional pearlite promoting alloying elements of manganese, copper, tin, nickel, and carbon have been assessed in a high silicon grade [8]. This non-peer reviewed investigation concluded that only tin caused a significant reduction in elongation [8]. The effects of carbon content at constant silicon was not significant small compared to other elements present [8]. The solid solution ferrite ductile iron was forgiving in its ability to tolerate pearlite and carbide/intermetallic promoting elements such as boron, phosphorus, copper, chromium, and molybdenum [8].

**WHAT IS PROPOSED THAT HAS NOT BEEN DONE BEFORE**

The influence of combined pearlite promoters on SSFDI.

**EXPERIMENTAL PROCEDURE**

The test heats will be produced in a 300 pound capacity coreless induction furnace to assess pearlite promoters (Table 1) and phosphorus (Table 2). The heats will be cast into a 100 mm wide step bar (Fig. 2) and into bars of 19 mm diameter x 200 mm long cylindrical bars (Fig. 3). The magnesium treatment will be done via the tundish method with a magnesium-ferrosilicon alloy. The cast bars will be sectioned and turned for tensile testing and the step block will be utilized for examining the microstructure and shrinkage tendencies of each alloy.
Figure 2. Step bar to be used for microstructural and shrinkage analysis of each alloy; risers may be modified.

Figure 3. Bar mold to be used for tensile testing of each alloy.

Table 1. Potential Test Matrix for Pearlite Promoters

<table>
<thead>
<tr>
<th>Trial</th>
<th>Cu</th>
<th>Mn</th>
<th>P</th>
<th>C</th>
<th>Si</th>
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</thead>
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<td>0.5</td>
<td>0.05</td>
<td>3.1</td>
<td>3.8</td>
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<tr>
<td>2</td>
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<tr>
<td>3</td>
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<tr>
<td>4</td>
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<td>5</td>
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<tr>
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<tr>
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<td>0.02</td>
<td>3.1</td>
<td>3.8</td>
</tr>
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### BENEFITS TO MEMBERSHIP

Currently many foundries attempting to produce SSFDI are having to pig large quantities of metal as they attempt the transition from traditional grades that rely on pearlite promoters such as Mn, Cu, Cr, Ni, and Sn for controlling the amount of pearlite in the matrix microstructure to a melt that does not have large amounts of these pearlite promoters. If the thresholds for pearlite promoting elements are better understood the foundries could better utilize their melting resources and have manufacturing cost savings. This understanding could also help with lowering costs of the charge make-up and lower cost scrap steel and returns could be used instead of higher cost virgin materials as long as the overall make up of the charge is below the maximum threshold for the pearlite promoters.

### GANTT CHART

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<th>Main Task</th>
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<td>Pours of pearlite promoters</td>
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<td>Mechanical Testing pearlite</td>
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<td>Redo necessary pours and testing</td>
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REFERENCES


