Ductile Iron Society Annual Award

Gene Muratore accepts the Ductile Iron Society Annual Award from President Pete Guidi
INTRODUCTION
The University of Alabama at Birmingham was involved in a project to determine the feasibility of using compacted graphite iron (CGI) in a commercial part. One of the project goals was to develop an ultrasonic velocity method to separate acceptable from unacceptable microstructures as a production quality control procedure.

Ultrasonic velocity is commonly used as a quality control technique in the production of cast iron. It is very sensitive to graphite shape, and can be determined inexpensively and quickly. Ultrasonic velocity is a function primarily of the modulus, and density of the material. The porosity size and distribution also affects ultrasonic velocity due to their effects on density, modulus and pulse wave shape. The velocity of a longitudinal ultrasonic wave through a material can be expressed as (Krautkrämer, 1983):

\[ v_l = \frac{E}{\sqrt{(1+\mu)(1-2\mu)}} \sqrt{\rho} \]  

Equation 1

where \( v_l \) is the longitudinal ultrasonic velocity, \( E \) is Young’s modulus, \( \rho \) is density, and \( \mu \) is Poisson’s ratio. Young’s modulus increases as the square of the density, i.e., as porosity decreases (Klima and Baaklini, 1984):

\[ E = E_0 \exp(-bP) \]  

Equation 2

Where \( E_0 \) is Young’s modulus for the nonporous material, \( P \) is volume fraction porosity, and \( b \) is a factor related to the pore size, shape and location. Poisson’s ratio generally increases with increasing density, but the effect is usually small.

The microstructure of cast iron consists primarily of ferrite, pearlite and graphite. The density difference between the iron matrix and graphite in cast iron produces a large impedance at the iron/graphite interface. Therefore, an ultrasonic wave traveling through the iron will react to the graphite in a manner similar to a pore. The matrix microstructure will influence ultrasonic velocity but to a much smaller degree than the graphite shape and number.

PROCEDURE
Effects of section shape, transducer frequency, contact method, and microstructure on velocity needed to be understood to provide a robust and accurate procedure. A variety of cast irons, primarily CGI, were collected from three production foundries to develop a set of standards for experimental and production control. Three shapes were produced from the supplied cast iron as illustrated in Figure 1. The Oak Box standard was designed to eliminate any interference from sidewall reflections to the ultrasonic wave. This design is used to produce the cleanest signal possible. Unfortunately, most production castings are unlikely to have a location that matches the relatively large diameter of the Oak Box standard so a smaller diameter standard was produced called a Working standard. Finally, a Lens shaped standard was produced to test for any effects caused by a work piece with a curved surface. The standards had surface finishes smoother than 50Rq.
The most common transducer frequencies used for castings range from 1-10 MHz so two transducer frequencies were tested: 2 and 5 MHz. Most production facilities use a non-contact technique to speed production and compensate for rough or irregular surfaces. In some situations, contact measurements are also made so in this experiment, velocities were calculated using both non-contact and contact methods. Figure 2 illustrates the tank and transducer arrangement used for the non-contact calculations. For the contact calculations, a delay line was used to remove any rattle caused by the main bang of the transducer, as illustrated in Figure 3. The delay line was made of wrought 6061 aluminum with a thickness of 0.5 in. (12.2 mm) and a diameter of 1 in. (25.4 mm).

Both setups used a Panametrics® 5800 pulser/receiver and a Tektronix® TDS210 digital oscilloscope. The two transducers were aligned on the same axis and powered by the pulser/receiver. Ultrasound was sent by one transducer and received by the other in a pitch/catch technique. The received ultrasonic signal was recorded on a digital oscilloscope for subsequent analysis.

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**Figure 1. Ultrasonic Standard Designs.**

**Figure 2. Apparatus for Measuring Ultrasonic Time-of-Flight Non-Contact on CGI Specimens.**
Time of flight was measured using both the first break and second peak of the ultrasonic signal as illustrated in Figure 4. First break is often used if the material being tested distorts the peaks such that an accurate measurement is difficult.

The ultrasonic velocity was calculated by dividing the specimen thickness by the time required for the signal to travel through the specimen. A reference signal was first recorded with the delay line between the two transducers. The test specimen and delay line were then put between the transducers and the signal captured. The transit time through the test specimen was determined by comparing the reference signal obtained with the delay line to the signal obtained with the delay line and specimen between the transducers. Multiple measurements were made to assure accuracy. A constant coupling pressure was maintained on the transducer-delay line-specimen system to assure that consistent signals were obtained.

A representative sample of each iron was polished using a procedure developed at UAB. Twenty-five images at 200X of unetched microstructure were recorded for each sample for graphite analysis. The microstructural images were analyzed using an image processing software package that measured a variety of characteristics including nodule count, surface area of graphite/volume of material (SV), shape factor, and percent nodularity. Shape factor was calculated using the following formula:

Shape factor = (4π*Area)/(perimeter)² Equation 3

Graphite particles with a shape factor greater than 0.65 were considered nodular (a perfect circle has a shape factor of 1).

No attempt was made to control either the chemistry or pearlite/ferrite content of the standard
The range of microstructures used in this study are presented in Figures 5 through 10 in the un-etched and etched condition. The graphite shape varied considerable over these samples as did the amount of pearlite/ferrite in the matrix.

**Figure 5. Microstructure of Foundry A CG Iron Standard #1962.**

(A) Unetched. (B) Nital Etch.

**Figure 6. Microstructure of Foundry A CG Iron Standard #2051.**

(A) Unetched. (B) Nital Etch.

**Figure 7. Microstructure of Foundry C CG Iron Standard #2489.**

**Figure 8. Microstructure of Foundry C CG Iron Standard #X72.**

**RESULTS AND DISCUSSION**
Effect of First Break Vs. Second Peak Velocity Determination

Both first break and second peak velocity measurements were made and typical comparisons are illustrated in Figure 11. The analysis showed that the first break velocity is about 0.005 in/μsec higher at velocities above 0.19 in/μsec and about 0.10 in/μsec higher at velocities below 0.19 in/μsec. These results indicate that both measurement methods performed well but if comparisons between castings are going to be made, ultrasonic velocity should be determined using the same time of flight criteria.

![Figure 9. Microstructure of Foundry C CG Iron Standard #W72.](image)

![Figure 10. Microstructure of Foundry B Ductile Iron Standard.](image)

Effect of Standard Shape

The effect of standard shape on ultrasonic velocity is illustrated in Figure 12. Due to material constraints, we had fewer Lens-shaped and Oak Box standards than Working standards. However, varying the standard shape within these limits did not significantly change the velocity response to microstructure. Side wall reflections did not influence or interfere with the thru velocity technique used in this study but may pose a problem if using multiple reflections in a thru-back method. The curved surface of the Len-shaped standards did not increase or decrease the pulse strength or shape.

Effect of Transducer Frequency

The effect of transducer frequency for contact and non-contact set-ups are illustrated in Figures 13 and 14 respectively on the working standards. In both cases, the velocity shifted upward as the transducer frequency was increased. For the contact measurements, the shift was less than 0.05 in/μsec while for the non-contact measurements, the velocity shifted up between 0.05 and 0.001 in/μsec with an increase in transducer frequency from 2 to 5 MHz. The shapes of the curve were unaffected. Velocity is independent of frequency in homogeneous materials as shown in Equation 1. Most materials however contain an inhomogeneous microstructure which will absorb and scatter the ultrasonic wave depending on the wave frequency. This scattering causes velocity to be dependent on frequency.
Effect of Transducer Coupling Method
The effect of non-contact versus contact transducer coupling methods are illustrated in Figure 15. The non-contact velocities were lower than the contact velocities and the differences were greater at higher velocities. The differences in velocity could come from a number of sources. Velocity calculations for contact measurements are straightforward with no other variables. Non-contact calculations require not only the thickness of the sample but the distance between the transducers and the ultrasonic velocity of the water. A water temperature variation of a few degrees can measurably change its velocity. The location of the transducers can also make accurate measurement of their separation difficult. Any error in these measurements can produce an offset from the contact velocity calculations.

Figure 11. Effect of Velocity Determination Method on Velocity.

Figure 12. Effect of Standard Shape on Velocity.
Figure 13. Effect of Transducer Frequency on Velocity-Contact Measurement.

Figure 14. Effect of Transducer Frequency on Velocity – Non-Contact Measurement.

Figure 15. Effect of Transducer Setup on Velocity

**Correlation of Microstructure Measurement to Velocity**

Percent graphite nodularity is typically specified to a level by the customer and charts exist that allow the foundry to quickly rate a microstructure. Image analysis methods also exist for characterizing graphite morphology. Careful image analysis of the graphite can provide less subjective results but this method is much more time consuming. Nodularity can be calculated using image analysis programs by selecting a shape factor value below which a graphite shape becomes non-nodular, such as was performed here. Other microstructural features can simultaneously be measured using image analysis including the average shape factor and the graphite surface per unit volume. Excellent correlations between graphite surface per unit...
volume (SV) and ultrasonic velocity have been made in the past (Patterson, 1979). However, this descriptor is also influenced by volume fraction and number density which do not affect ultrasonic velocity as strongly as shape.

Figures 16, 17 and 18 show the relationship between velocity and nodularity, shape factor and graphite SV. Figure 16 plots ultrasonic velocity at 2 MHz versus percent nodularity for all standards using non-contact. The correlation between nodularity and velocity was above 90% for an exponential fit and these results are excellent for irons that varied widely in chemistry and matrix structure. These results indicate that the velocity measurement should provide assistance in separating acceptable and unacceptable graphite structures in CG iron parts. The results were similar for the average shape factor as illustrated in Figure 17 with a correlation above 90% for an exponential fit. The relationship between graphite SV and velocity was not as good and these results are illustrated in Figure 19. Surface per unit volume appeared to contain two populations and is obviously affected by other unaccounted for microstructural features such as variations in the volume fraction or number density of graphite particles.

SUMMARY AND CONCLUSIONS
The University of Alabama at Birmingham was involved in a project to determine the feasibility of using compacted graphite iron (CGI) in a commercial part. One of the project goals was to develop an ultrasonic velocity method to separate acceptable from unacceptable microstructures as a production quality control procedure. Effects of section shape, transducer frequency, contact method, and microstructure on velocity needed to be understood to provide a robust and accurate procedure. A variety of cast irons, primarily CGI, were collected from three production foundries to develop a set of standards for experimental and production control. Three shapes were produced from the supplied cast iron.

Velocity measurements were made using both 2 and 5 MHz transducer frequency, contact and non-contact methods and different size and shaped standards. Varying the standard shape within the limits of this study did not significantly change the velocity response to microstructure. Side wall reflections did not influence or interfere with the thru velocity technique used in this study but may pose a problem if using multiple reflections in a thru-back method. The curved surface of the Len-shaped standards did not increase or decrease the pulse strength or shape.

Figure 16. Relationship Between Graphite Nodularity and Velocity.
Small but significant shifts in velocity were found with changes in transducer frequency. For the contact measurements, the shift was less than 0.05 in/μsec while for the non-contact measurements, the velocity shifted up between 0.05 and 0.001 in/μsec with an increase in transducer frequency from 2 to 5 MHz. The shapes of the curve were unaffected.

Similar to transducer frequency, small differences in velocity were observed with differing transducer coupling methods. The non-contact velocities were lower than the contact velocities and the differences were greater at higher velocities. The differences in velocity could come from a number of sources. Velocity calculations for contact measurements are straightforward with no other variables. Non-contact calculations require not only the thickness of the sample but the distance between the transducers and the ultrasonic velocity of the water. A water temperature variation of a few degrees can measurably change its velocity. The location of the transducers can also make accurate measurement of their separation difficult. Any error in these measurements can produce an offset from the contact velocity calculations.

The correlation between nodularity and velocity was above 90% for an exponential fit and these results are excellent for irons that varied widely in chemistry and matrix structure. These results indicate that the velocity measurement should provide assistance in separating acceptable and unacceptable graphite structures in CG iron parts. The results were similar for the average shape factor with a correlation above 90% for an exponential fit. The relationship between graphite SV and velocity was not as good. Surface per unit volume appeared to contain two populations and is obviously affected by other unaccounted for microstructural features such as variations in the volume fraction or number density of graphite particles. These results indicate that ultrasonic velocity should provide a valuable tool for separating acceptable and unacceptable graphite structures in CG iron.

Figure 17. Relationship Between Graphite Shape Factor and Velocity.

Figure 18. Relationship Between Graphite SV and Velocity.
Refractory Considerations for Melting Ductile Iron

Pete Satre
Manager, Product Services

Allied Mineral Products
Melting Equipment

- Primary Melting - Coreless
Silica Lining Wear

- Reduced lining life due to
  - Deeper lining saturation
  - Buildup
  - More pronounced elephant’s foot wear
  - Floor spalling
  - Top cap separation
Lining Saturation

- Deep saturation can occur behind lining hot face
Low Porosity Silica Refractory

- Silica refractories with higher density/lower porosity can reduce saturated layer
- Bond level (boron oxide or boric acid) must be matched to application temperatures
- Alloy additions should be made at midlevel or higher in furnace when charging furnace
Buildup can be a result of charging a high percentage of ductile iron remelt or from some ferroalloy additions.

A supplemental flux, such as Redux, can be used to control buildup.

When removing buildup, avoid mechanical damage to the sidewall.
Elephant’s Foot Wear

- Elephant’s foot wear occurs most often in main frequency (heel melting) furnaces.
- The wear is more acute when running ductile iron, especially when the average tap temperature is high.
Elephant’s Foot Wear

- Lining wear occurs in specific areas of the furnace.
- Optimization of installation, sintering, temperature control, and charging are important process variables.
- Taper shave can be a repair option.
Floor Spalling

- Spalling is due to insufficient sinter temperature in the floor in high powered, medium frequency furnaces.
- Poor sintering results in increased saturation and differential expansion spalling.
Floor Wear

- Fused silica or zircon addition can reduce thermal expansion on the floor area.
Silica vs. Fused Silica
Top Cap Separation

- Top cap separation is due to material expansion differences, and sharp thermal gradients.

- Materials used
  - Alumina-Silicate Dry Vibratables
  - Fused Silica Dry Vibratables
Castable Top Cap Repair
Castable Top Cap – Large Furnace
Fiber-Reinforced Refractory

- Crack propagation is inhibited by the use of metallic fiber as a toughening mechanism.

- Used for many years in castables, but how about in linings of coreless furnaces?
Metallic Fibers – Now in the Lining?

- Reduction in thermal cracking in top cap and working lining
- Increased toughness can decrease mechanical wear
Coreless Melting Process Variables

- Charge material
- Operating pattern
- Process temperature control
- Installation and sintering of silica lining
Influence of Graphite Morphology and Matrix Structure on Fatigue Strength and Wear Resistance of Ductile and Austempered Ductile Iron

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ABSTRACT
The effect of graphite morphology and matrix structure on both fatigue strength and wear behavior of the unalloyed ductile iron (DI) and ADI were studied. The graphite morphology has been changed from spheroidal as in the as-cast condition to ellipsoidal shape after applying a forging process. The matrix structure changed from pearlite-ferrite as in the as-cast and forged conditions to an ausferrite structure that was produced by applying an austempering heat treatment at 400 °C for 1 hour. Optimum mechanical properties were achieved for the austempered ductile iron (ADI), where it obtained an ultimate strength of 1060 MPa and hardness value of 390 HB. The lowest value of tensile strength and hardness were reported for the as-cast DI of 620 MPa and 236 HB, respectively. ADI also showed optimum values of fatigue strength and wear resistance, while the forged DI had a lower fatigue strength value due to the harmful effect of graphite ends that facilitate crack initiation and propagation in the matrix. Forged DI showed better wear resistance than the as-cast DI due to the matrix strengthening effect observed by forging. It was found that optimum mechanical properties can be obtained by using ADI rather than the as-cast and forged DIs.

INTRODUCTION
The effect of graphite configuration and matrix structure on static and fatigue properties of cast iron has been the subject of previous investigations [1]. The fatigue performance of ductile iron depends on quantity, size and shape of the nodular graphite as well as its interaction with the matrix structure. Riposan and Chisamera [2] compared the fatigue behavior of various cast irons containing different graphite configurations. Ductile iron exhibited the best fatigue resistance, while gray iron displayed relatively poor fatigue strength. The superior performance of ductile iron over gray iron has been attributed to the dissimilarity in graphite morphology between the two materials. In recent years, there has been significant interest to increase the fatigue strength of ductile cast iron by strengthening its matrix [3]. This can be achieved by applying the austempering heat treatment to produce the austempered ductile iron (ADI), by performing mechanical deformation on the ductile iron or through a surface hardening treatment such as shot peening or roller burnishing [4]. Janowak et al. [5] concluded that fatigue limit is increased with increasing matrix hardness, pearlite content and graphite nodule count.

The purpose of this study was to explore the correlation between the fatigue properties of as-cast ductile iron, forged ductile iron and austempered ductile iron to the microstructural parameters of graphite nodule configuration and matrix structure.

EXPERIMENTAL PROCEDURE
The material used in this investigation was unalloyed DI (GGG60) nodular cast iron. The chemical composition of this material is 3.63% C, 2.32% Si, 0.51% Mn, 0.023% P, 0.014% S, and 0.27% Cu. One-inch Y-blocks were cast in a medium frequency induction furnace. The bottom of the cast Y-blocks were cut into slabs and divided into three groups. One group was tested in the as-cast condition with no change. The second group was subjected to the austempering heat treatment thermal cycle shown in Fig. 1. The third group was hot forged to an 80% reduction in area. The fatigue strength was determined using the S-N curve approach per ASTM standard E-466 [6]. The rotary bending fatigue test technique was used to evaluate the
fatigue strength of the studied material. Smooth cylindrical specimens were machined from the test slabs. The dimensions for these specimens are given in Fig. 2. The specimens were loaded under constant stresses, and the number of cycles for failure was recorded. Adhesion wear testing was carried out in a dry condition against a hardened stainless steel ring with a hardness of 63 HRC. The wear test was carried out using block-on-ring testing machine at different rotating speeds of 100, 150, 200, 250 and 300 rpm under a constant applied load of 150 N for one hour. Dry wear of specimens was measured as a function of weight loss with a sensitivity of 0.1 mg. The microstructural analysis of the samples was completed using optical metallographic methods. The fracture surface of the fatigue samples and the worn surface of the wear samples were examined by using scanning electron microscopy.

![Fig. 1 Thermal cycle of the austempering heat treatment](image1)

![Fig. 2 Configuration of the rotary bending fatigue sample](image2)

**RESULTS AND DISCUSSION**

**Metallographic investigation**

The microstructure of the three different forms of the studied ductile cast iron (DI) is shown in Figs. 3 a-d. The as-cast DI structure consists of nodular graphite within a pearlitic matrix with about 15-20% ferrite (Fig. 3-a). The forged DI has the same matrix structure as the as-cast DI, but the difference lies in the graphite form. The forging process deformed the as-cast DI spheroidal graphite to oval shape with acute edges in both sides (Fig. 3-b). It is interesting to note that the deformed graphite is still surrounded by the ferrite phase, as illustrated at a higher magnification in Fig. 3-c. The austempered ductile iron (ADI) shows another ausferrite matrix structure, in which the matrix consisted of acicular ferrite and high carbon austenite (Fig. 3-d). The austempering heat treatment process does not affect the graphite form. The volume fraction of retained austenite in ADI was measured using XRD and found to be approximately 21% with the remainder of the matrix being acicular ferrite (Fig. 3-d.)

![Micrographs of ductile cast iron](image3)
a. as-cast DI  X100  
b. forged DI  X100
Mechanical Properties
The mechanical properties of the different forms of DI were studied. The fatigue behavior and wear characteristics of each type of DI were thoroughly investigated. Figure 4 shows the hardness values of the three different forms of DI. It is obvious that ADI obtains the maximum hardness value of 390 HB while the as-cast DI demonstrates the lowest value of 236 HB. The hot forged DI develops a higher hardness value of (250 HB) than the as-cast DI due to the work hardening effect from the forging process. The tensile properties of the investigated DI were also determined, as seen in Fig. 5. It is clear that the tensile strength behavior of the three forms of DI follow the same trend as the hardness, where ADI showed the maximum tensile strength and the minimum was for the as-cast structure. It is known that mainly the matrix constituents determine the tensile properties of ductile iron. As a result, the pearlitic-ferritic matrix should obtain lower tensile strength than the ausferritic one, because ausferrite is considered to be a homogenous, strong, fine structure. Therefore, ADI has a high tensile strength value of 1060 MPa, while the lowest value of 620 MPa was exhibited for the as-cast DI due to the low strength value of the pearlite and ferrite matrices. On the other hand, the forged DI shows a relatively higher strength value compared to the as-cast DI due to the effect of work hardening applied on the matrix by the forging process. A maximum elongation of 17% was recorded for the as-cast DI and the lowest one was reported for the forged DI (Fig. 6). The reduction in the ductility of the forged DI can be attributed to the acute edges formed at the ends of the ellipsoidal shaped graphite, which can easily initiate cracks that can propagate in matrix. It could be said that the forged DI looks somewhat like the gray iron, which has very low or no ductility. On the other hand, ADI shows better elongation (10%) than the forged DI, but lower than the as-cast DI. The ductility of ADI can be observed from the high carbon austenite existing in matrix as well as the homogeneity and microstructural scale of the ausferrite matrix [7,8].
Fatigue behavior

Ductile iron became a very attractive engineering material because of high fatigue strength compared to its tensile properties [9]. Thus, it is very important to understand the factors affecting the fatigue properties of ductile iron, such as graphite shape, nodule count and size, matrix structure, and thermal-mechanical surface hardening (i.e. heat treatment, shot-peening, surface rolling), etc [10-12 & 18-21]. Unfortunately, there is no published work on using the forging process to change the DI graphite nodules to elliptical shape and its effect on the fatigue strength. Figure 7 shows the S-N curve for three different types of DI. Results show that the highest fatigue limit is obtained for ADI and the lowest one observed is for the forged DI. This preliminary result shows the effect of both matrix structure and the graphite shape on fatigue properties of DI. The main reason for decreasing the fatigue strength of the forged DI may be attributed to the elliptical graphite shape formed inside the pearlitic-ferritic matrix and its inherent fracture mechanics. Figure 3-c shows the elliptical graphite edges, which have harmful effect on fatigue property of the forged DI. Therefore, the main reasons for this harmful effect can be explained as follows:

- High stress concentration may arise at the edges of the elliptical-formed graphite, which can facilitate fatigue crack initiation and propagation under cyclic load.
- The length of the elliptical graphite is increased; therefore it could be considered as an internal defect that decreases the fatigue strength.
- The distance between edges of the elliptical graphite is shorter than that in the as-cast condition with spheroidal graphite. This may aid in faster fatigue crack propagation.

In spite of the matrix structure, the forged specimen is much harder and has more strength than the as-cast DI. However, the fatigue limit of the as-cast DI is higher than the forged one. This result can affirm that the graphite shape plays a very important role in determining the fatigue strength of ductile iron.

On the other hand, the ADI structure has a higher fatigue limit than both the as-cast and forged DI. This is due to the effect of the fine-grained lath microstructure that also contains some austenite (ausferrite). This high carbon austenite can be transformed into martensite as a result of the applied work hardening during the fatigue test. Such transformation occurring in the plastic zone ahead of the crack would relax the stress concentration at the crack tip [13-15]. The accompanying volume change (transformation of high carbon austenite to martensite) also encourages plastically induced crack closure to occur, reducing the fatigue crack rate and
consequently increasing the fatigue strength. Therefore, the ausferrite matrix structure plays a very important role in determining the fatigue strength of ADI when compared to the as-cast DI that has the same graphite shape but different matrix structure. As a result, the ausferrite structure develops higher fatigue strength than the as-cast DI. In conclusion, the matrix structure and graphite shape play an important role in determining the fatigue strength of ductile iron. Therefore, for obtaining a high fatigue limit, the as-cast DI should be austempered to produce ausferrite with a nodular graphite shape.

**Fracture surface study**

Figure 8 shows a typical fracture surface of the investigated samples. In general, the crack initiation and fracture feature are associated with the matrix constituents and imperfections at the surface of the specimens. As shown in Figure 8-a, the as-cast DI has a cleavage fracture surface due to the existence of a pearlite matrix, which is normally fractured in a brittle mode. The fracture surface of the forged DI illustrates the effect of the graphite shape in developing fatigue crack growth in the matrix, as shown by the arrow in Figure 8-b. These deformed graphite nodules can easily initiate a crack through cyclic loading and then the crack can propagate to the next nodule. This observation is in agreement with the obtained results, in which the forged DI demonstrated the lowest fatigue limit as a result of its graphite shape. Moreover, the forging process destroyed or fractured some graphite nodules, which in turn they can extensively pull out from the matrix. On the other hand, ADI obtained quasi-cleavage fracture (Fig. 8-c.) The observed dimples in this fractography indicating the locations of the existing retained austenite, while the small cleavage areas indicate the bainitic matrix locations, which contain Fe3C as a constituent of its structure.

**Wear characteristics**

The results of wet abrasion wear tests carried out at different rotating speed ranging from 100 to
300 rpm are shown in Fig. 9. The wear rate was calculated as the weight loss (gm) per testing time (sec). As expected, the wear rate increased with increasing the rotating velocity due to the increase in shear stress over the specimen surface. This increase in shear stress leads to an increase in the surface temperature and softening of the face layer of the specimen so it can easily be removed by an adhesion wear mechanism, resulting in an increased wear rate. It can be seen that the lowest wear rate was recorded for the ADI, while the highest wear rate was observed for the as-cast DI. The forged DI wear rate is relatively lower than the as-cast DI. The difference in the wear rate may be attributed to the role of both graphite nodule shape and matrix hardness [16]. It is known that the ADI with the ausferritic matrix has higher hardness than the as-cast and forged DI with pearlitic-ferritic matrices. Generally, ADI shows an increase in hardness of about 40% than the as-cast DI and about 36% than the forged DI. This is the reason that the wear rate of ADI is lower than the other two studied conditions. On the other hand, the matrix strengthening effect due to forging caused the wear rate of the forged DI to be lower than the as-cast DI. In the light of this study it is safe to say that the forging strengthening effect is not enough to decrease the wear rate of the as DI and that the austempering heat treatment is necessary to obtain ausferritic matrix and subsequently increase the wear resistance than the as-cast and forged DI. Furthermore, the effect of the graphite shape is not as clear in determining the wear rate of the studied cases, as is the effect of matrix. Generally, it is known that the graphite has very important role in forming a graphite layer over the contact surfaces, which in turn will act as a lubricant layer that decreases the wear rate [17]. This effect is clear in the difference between the wear rate of both the as-cast DI and the forged one. The as-cast DI has a spheroidal graphite shape that has a geometrically larger surface area as compared to the forged DI that has ellipsoidal graphite shape. This factor of surface area is very important in forming a thick graphite layer between the specimen and the rotating ring in order to protect the specimen from adhesion wear. As a result, the forged DI should obtain a higher wear rate than the as-cast DI. However, the deformed matrix (or strengthening of matrix by forging) dominates over the graphite shape difference, resulting in enhancing the wear resistance of the forged DI as compared to as-cast DI.

![Fig. 9 Wear rate characteristics of the investigated ductile iron](image)

**Morphology of worn surfaces**

The worn surfaces of the investigated specimens were examined using SEM to elucidate the mode of the wear process. Figures 10 a-c shows the worn surfaces of the three different forms of ductile iron, in which the testing velocity was 250 rpm. As shown in Fig. 10-a, ADI obtains the lowest surface deterioration, where the worn surface is characterized by a scratch mechanism due to adhesion wear. This observation coincides with the results obtained for ADI. ADI has a high hardness value, which in turn can well resist the adhesion wear by causing only some scratches on the worn surface. For the as-cast and forged DIs that have lower hardness values, the worn surfaces exhibit another phenomenon. The worn surface of the as-cast DI shows the main basic modes of a severe wear condition (Fig. 10-b.) This severe wear mode can also be described as a lamination and delamination wear mechanism. This mechanism of wear produces lamella automatically from the faced surface due to the high-applied shear stress (as a result of severe condition) over the worn surface. These layers or lamellas will fail out as wear debris from the surface (which is known a delamination mechanism). This process can also produce a worn surface with a rougher wear scar and consequently a higher wear rate. The worn surface (Fig. 10-c) of the hot forged DI demonstrates the same feature (lamination and
delamination mechanisms) as the as-cast DI with a less rough worn surface.

![SEM images](image_url)

**Fig. 10 - SEM of the worn surfaces observed at revolution speed of 250 rpm**

**CONCLUSIONS**

Based on this study, it may be concluded that:

1. The as-cast and hot forged DI had a microstructure of pearlite-ferrite, but the forged DI showed elongated graphite nodules. The ADI structure had an ausferrite matrix with approximately 21%-retained austenite.
2. ADI had the highest hardness value of 390 HB. The as-cast DI demonstrated the lowest value of 236 HB, while the forged DI had a slightly higher value (250 HB) than the as-cast DI.
3. The tensile properties showed the same trend as the hardness, where ADI developed the highest tensile value of 1060 MPa and the lowest value of 620 MPa was recorded for the as-cast DI.
4. The lowest elongation was reported for the forged DI as a result of the edges formed at the graphite ends, and the highest value of 17% was obtained for the as-cast DI.
5. The highest fatigue strength was observed for the ADI, while the lowest value was reported for the forged DI due to the harmful effect of graphite ends that easily initiate cracks in the matrix.
6. The maximum wear resistance was reported for the ADI and the minimum one was observed for the as-cast DI. Forged DI obtained a relatively better wear resistance than...
7. The ADI worn surface showed a scratched wear mechanism; while both as-cast and forged DIs exhibited lamination and delamination wear mechanisms.
8. The optimum wear resistance and fatigue strength of DI can be achieved by applying an austempering heat treatment rather than the forging process.

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REFERENCES


Production of Iron Castings Utilizing a New Generation of Feeding Systems

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ABSTRACT
A new generation of feeding systems has been developed to increase the pattern yield and reduce casting scrap by providing a consistent feed profile combined with ease of application and removal.

The KALMINEX K sleeve/core feeding system design was developed for use in medium-pressure, automated, horizontal, greensand molding lines. The design objectives were for the system to have the feeding performance of an exothermic/insulating insert sleeve, the strength of a ram-up sleeve, and the knock-off characteristics of a spot feeder. The result is a novel feeding system development.

This paper describes the development, optimization and testing of the sleeve and compressor core designs and integration. Foundry trials were conducted at Rochester Metal Products to further optimize the application of this novel feeding system. The casting layout and trial results are also discussed in detail.

INTRODUCTION
There is a distinct set of challenges the foundry encounters when producing iron castings on automated horizontal greensand molding machines. Most castings require the use of feeders to deliver liquid metal to the casting as it solidifies. In some cases, feeding systems such as riser sleeves can deliver the metal more economically than a traditional greensand riser. The application of the riser sleeve plays a major role in this economic equation.

Typically, a “riser bob” makes an impression on the cope face of the mold. The riser sleeve is then inserted into the formed cavity, and the mold is closed. This application requires adequate cope access and dimensionally accurate sleeves and riser bobs.

A different, more robust approach is to ram-up the feeding system during the molding. Sleeves used in this manner must be strong enough to withstand high molding pressures without damage. Cost justification for these types of applications can be difficult, due to the requirement for specialized feeding systems.

Standard insert sleeves can fail in medium pressure ram-up applications. Stronger sleeves are generally required for these applications. Increased sleeve strength is typically achieved by increasing the density of the sleeve material, potentially resulting in reduced insulating capability and increased cost.

The compromises inherent in using standard insert sleeves in ram up applications highlighted an obvious market need for an innovative feeding system design. A carefully engineered project was initiated in response to this market need. The three principal goals were to develop a feeding system: (a) to feed as well as a standard exothermic/insulating insert sleeve, (b) to withstand medium-pressure molding machines during ram-up, and (c) to allow for easy riser removal.

DEVELOPMENT
The design of the sleeve had to be optimized to obtain the necessary strength and feed performance for a standard exothermic/insulating insert sleeve recipe. It was hoped that the strength of the sleeve could be increased not only through the use of a compressor core, but also through a novel design of the sleeve itself. Engineering fundamentals such as strength of...
materials, mechanical design, and heat transfer were rigorously applied to develop a feeding system capable of serving the identified market.

The development efforts are divided into two sections. The sleeve and core designs were optimized individually. Additional engineering was required to integrate the individually optimized sleeve and core.

**Sleeve Design Optimization**

The design optimization of the sleeve geometry was carried out using MAGMASOFT casting simulation software. Several sleeve designs were evaluated at multiple wall thicknesses, shapes and height to diameter ratios, and compared against the baseline performance of a standard-shaped 2.5”x3.75” exothermic/insulating insert sleeve. The simulated test casting was a 4” steel cube. Some example results are shown in Figure 1.

![Figure 1: Example feed safety margin results for several sleeve designs](image)

The optimized sleeve design is the domed sleeve displayed in Figure 1. This sleeve design is predicted to have an initially flat feed and a broad feed pipe. The thicker walls at the base of the sleeve provide greater insulation in this area. This design slightly outperforms the standard insert sleeve.

**Core Design Optimization**

Breaker cores used in ram-up applications have several requirements. First, they must not fail during molding, and they should prevent the sleeve from failing as well. Secondly, they must provide a notch or stress concentration near the contact of the riser to allow the riser to be easily removed.

Traditional breaker core technology can meet some of these requirements effectively, but may suffer from breakage and are limited in some applications due to their relatively large contact requirements. Ideally, the core footprint should be minimized to increase applicability. To meet all these requirements, recently developed metal core technology was used.

The metal core is designed to collapse as the mold is compacted. Figure 2 shows a picture of a compressed and uncompressed metal core.

![Figure 2: Compressed and uncompressed metal breaker cores](image)

Typically, a flat flange is used to attach the metal breaker core to the sleeve material. As was the case in the sleeve design, it was desired to optimize the design of the metal compressor core for this application. This was accomplished by conducting a stress-strain analysis using Abaqus, a finite element analysis program that models the stress-strain behavior of geometries.

As a baseline for the study, a first generation metal breaker core with a flat flange was modeled. The compression of this core and the stresses imparted to the sleeve material were simulated. Material properties of the core and sleeve were included in the model. Figure 3 illustrates these stress results as a result of core compression.
Figure 3: Stresses in the sleeve during collapse of the metal core

The blue area represents the sleeve material, and the thin gray line is the cross-section of the metal compressor core. The green and yellow colors represent areas of elevated stress in the sleeve material near the inside corner. As the core compresses, the stress is concentrated on the inside corner of the sleeve. This “point stress” could cause the sleeve material to fracture in this area.

For an ideal design, the force would be evenly distributed throughout the entire bottom surface of the sleeve rather than in a localized area. Evenly distributing the force across the bottom surface area reduces the maximum pressure imparted to the sleeve, thus effectively increasing the strength of the design. Because the imparted pressure is equal to the force/area, increasing the area in which the force acts upon is critical in achieving a lower pressure at the base of the sleeve.

A further refinement was to engineer the design such that the forces imparted to the sleeve material resulted in material compression rather than tension or shearing. This can be achieved by changing the flat interface between the core and sleeve to a beveled design. As shown in Figure 4, a 30-degree angle was incorporated in the core/sleeve design.
The stress results in Figure 4 show more evenly distributed stresses on the outer side of the sleeve. It should be noted that the model of the core was drawn with an angle slightly greater than that of the sleeve, and did not touch the sleeve material at all points along the sleeve/core interface. Stresses would have been more evenly distributed had the angle of the core and sleeve been equal. The angled core imparts approximately one half of the stress to the sleeve base as compared to the first generation metal core design.

**Integrated Design – KALMINEX K**

The simulation analyses run on the sleeve and the compressor core provided a theoretical solution. Solidification modeling showed that the sleeve design having a rounded top and thick walls at the base provided the optimal balance between performance and practicality. Stress simulations of the metal core showed that angling the flange of the core greatly reduce the maximum stress on the base of the sleeve.

A 30-degree bevel was added to the base of the thick-walled sleeve and metal core. This design was thought to provide a good combination between thermal performance and strength. Figure 5 below shows a prototype of this design.

**TESTING**

A series of tests were developed and conducted to confirm the compression and feed performance of the concepts developed and optimized using the various simulation tools.

Strength testing at the University of Northern Iowa’s Metal Casting Center (UNI) was done to determine if the new sleeve/core prototype could withstand molding pressures as well as existing ram-up, slurry sleeve technology. Feed performance testing was also conducted to determine if the sleeve could perform as well or better than an existing exothermic/insulating insertable riser sleeve technology.

**Strength Testing**

Molding tests were conducted to determine the relative strength of the sleeve/core prototype. Molds were made using an adjustable pressure Herman molding machine. Figure 6 shows a picture of the machine.
A wooden pattern plate was bolted onto a steel carriage assembly. Four separate sleeves/cores were set on the pattern plate, as shown in Figure 7.

After the sleeves were set on the pattern, approximately 2” of sand was riddled into the flask and evenly distributed over the pattern plate. Then the remainder of the flask was filled with sand. At this point, the mold was compressed to a prescribed pressure. The mold was then excavated in order to observe the condition of the sleeves.

Initially, a low pressure was used for the experiment. The pressure was then systematically increased over a defined range to simulate medium pressure horizontal molding applications, as shown in Figure 8.

Sleeve/Core Prototype Existing Ram Up Sleeve
The metal core compressed as designed, and both sleeves maintained structural integrity, thus satisfying the strength and molding project requirements.

The sleeves were also tested at molding pressures that exceeded the defined target market and objectives for this project. These tests were run for completeness, and damage occurred in both sleeves at similar high pressures. Figure 9 shows these results.

**Feed Testing**

Feeding tests were conducted to determine the relative thermal performance of the sleeve/core prototype. A standard 2.5”x3.75” exothermic/insulating insert sleeve with a traditional silica sand breaker core was used as a baseline comparison.

Feeding tests were conducted at UNI. Both insert and ram-up sleeves were tested on several cube sizes. The castings were poured with ductile iron. The cubes and risers were sectioned in half, and the feed safety margin was measured.

The figure below shows a representative sample of sectioned cubes and risers for both insert and ram-up sleeves. In the example shown, the 4.9” cube was the largest casting tested, and was selected to evaluate the maximum performance of the sleeve.
In all cases, the sleeve/core prototype ram-up feeding system performs slightly better than the standard insertable riser sleeve. In addition, the prototype design fed the cubes consistently with no negative safety margins. Results from the strength and feed tests confirmed that the sleeve/core development objectives were met successfully. Production tooling for sleeve and core was designed and the resultant product will be manufactured with the name KALMINEX K.

PRODUCTION TESTING

After testing was completed in a laboratory-foundry setting, a production facility was sought for conducting further testing. Rochester Metal Products, a world-class iron foundry, was approached for beta testing.

Rochester Metal Products began manufacturing gray iron castings in 1937 as a captive supplier to two manufactures of hand-push lawn mowers, and is currently selling both ductile and gray iron castings to over 250 non-captive customers. At present the foundry employs approximately 365 people and the facility spans more than 200,000 square feet.

The foundry is comprised of two specialized manufacturing areas; the Hunter Molding area is dedicated to the production of Gray Iron castings and the Disamatic Molding area is dedicated to the production of ductile iron castings. Total melt production from both areas is in excess of 80,000 tons per year.

The Hunter Molding area is comprised of four molding lines, a HMP 10 (14” x 19” flask), a HMP 20H, a HMP 20E and a HMP 20D (all 20” x 24” flasks). The iron is melted in two Ajax 1,500 KW Jet Flow 3.0 ton/ hour Electric Channel Induction Furnaces and one 3,000 KW Ajax/Duca 6.0 ton/ hour Electric Channel Induction Furnace. Gray Iron alloys of Class 25, Class 30 and Class 35 are all produced with a per day casting capacity of 70 + Net Tons. The Hunter Molding area produces diverse casting types ranging from Water Pump and Compressor Housing to Pulleys and Bearing Housings. Casting sizes range from 1 lb to 50 lbs.

The Disamatic Molding Facility is comprised of two Disamatic MK5B Molding Machines. The iron is melted in two Brown Boveri 11 ton per hour Coreless Melting Furnaces and is poured using Duca Pressure Pour Furnaces with Selcom automatic pouring controls. Ductile Iron grades of 65/45/12 (as cast), 80/55/06 (as cast) and 60/40/18 (heat treated) are produced with a capacity of 166 + Net Tons of castings per day. Casting types range from Brackets, Clamps, Fittings, Pulley and Housings and have a size range of 1 lb to 40 lbs.

A bearing housing casting produced in the Hunter molding area was selected for beta testing the new sleeves. This bearing housing is produced in Class 30 gray iron and has a cast weight of 44.08 lbs. The pour weight of the system is 79.08 lbs., resulting in a yield of 56 %.

The molding machine used is a Hunter HMP 20D. (The production target pouring temperature is 2525 +/- 25 deg. F. and the target pouring time is 16 seconds). The production pattern utilizes a pressurized gating and filtration system. The filter is positioned horizontally in the drag mold.
and utilizes a cope to drag cross-over to allow the metal to flow through the filter. A drag and cope runner bar is utilized to connect the gating system to the casting cavity and to the single greensand riser.

Figure 11 shows the current layout of the casting and rigging.

Figure 11: Original pattern layout

This pattern was modified to accept a KALMINEX K123 feeding system for beta-testing. The drag pattern was modified to include a non-pressurized filtered gating system. A stepped drag runner bar was utilized to ensure equal laminar metal flow through each ingate and into the casting cavity. A locating pin for the sleeve was attached to the cope pattern.
During testing, the drag fill and squeeze process was carried out as per normal production molding methods. After the match plate rotated to present the cope, the machine operator placed the feeding system onto the locating pin. Figure 13 shows the sleeve on the cope pattern plate.

The pattern plate was then shuttled to the right and the cope fill and squeeze process was completed. During the mold squeeze, the design of the compressor core allowed the metal core and sand to compress. This formed a breaker core of densely packed sand and a metal notch. The initial height of the metal core was 1.007”, and the compressed breaker core thickness was measured as 0.69”, or 31% compression. Figure 14 shows the fracture plane from the compressed metal core.

During shakeout the reduced breaker core diameter combined with the unique under cut design of the compressor core notch allowed for easy riser removal. In many instances the riser falls off during shakeout. Figure 15 shows the feeding system after shakeout with core fully compressed. Care was taken to prevent the riser from falling off during shakeout. A sectioned feeder is also presented and shows good quality, flat feed performance.
Figure 15: Riser at casting surface

During the trials several castings were retained for sectioning, and the castings were defect-free with no evidence of primary or secondary shrinkage.

The pour weight for the modified system was 67.0 lbs (reduced from 79.08 lbs) producing a pattern yield 65.8% (increased from 56%). Figure 16 shows a picture of the casting, gating, and riser.

Figure 16: Modified casting layout

The beta-testing trial at Rochester Metal Products confirmed that KALMINEX K could be successfully applied in a production setting. The feeding system met the objectives set forth at the onset of the project. It withstood the ram-up molding pressures, successfully fed the casting, and was easily removed from the casting during shakeout.

CONCLUSIONS

Automated, horizontal, greensand molding machines present a special challenge for feeding systems. In the past, sleeve recipes were altered to make conventional sleeve shapes denser, stronger and more robust. These compromises often resulted in sleeves that did not perform as well and/or were more expensive than their insert sleeve counterparts.

This market need was recognized and a project was designed to develop a sleeve that would have the feed performance of an insulating/exothermic insert sleeve, the strength of a ram-up sleeve and the knock-off characteristics of a spot feeder. The project resulted in a fully engineered sleeve called KALMINEX K that is a truly a novel development, with patent pending.

This new generation of feeding systems has been extensively tested for strength, feed and
knock-off performance and has met and/or exceeded all of the design criteria both in laboratory tests and in foundry trials.

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The Ductile Iron Society 2006 Fall Meeting will be held in Monterey, Mexico in October. The meeting will feature tours of Blackhawk de Mexico, CIFUNSA and Grede Proeza along with a full technical program. The exact dates and the host hotel will be announced later.