High Si-Mo Ductile Iron: Views from Users and Producers

High silicon molybdenum ductile iron is fast becoming the auto industry's choice for construction of high-performance exhaust manifolds.

Glen Weber, Ford Motor Co., Dearborn, Michigan
Greg Faubert, Chrysler Corp., Auburn Hills, Michigan
Mike Rothwell and Andrew Tegg, Crede Foundries, Inc., Milwaukee
David J. Wirth, Berlin Foundry (Citation Corp.), Berlin, Wisconsin

Due to the EPA's increased emission control standards, the U.S. automotive sector requires exhaust manifolds that have strength at high temperatures, are resistant to oxidation and have low expansion during use. High silicon molybdenum (Si-Mo) ductile iron has evolved as one of the most beneficial alloys for optimizing cost and quality with these requirements.

At this time, there is no national standard (ASTM or SAE) for the production of high Si-Mo, but the material specifications typically agreed upon by the customer and producer are carbon (C) at 3.04-3.4%, Si at 3.75-4.25%, and Mo at 0.5-0.7%. The C content is lower than ferritic ductile iron because the high Si content maintains the iron hypoeutectic-eutectic composition and prevents graphite flotation. Si is in the range of 3.75-4.25% enabling good oxidation resistance at temperatures above 1200°F (649°C). The Si forms a protective oxide layer, reducing grain boundary oxidation, and Mo increases both high-temperature yield properties and creep resistance of the material.

The growing market demand for high Si-Mo exhaust manifolds has encouraged more foundries to utilize the alloy. However, the successful foundries will be those that can consistently produce high Si-Mo castings at competitive prices. The challenge is to develop a successful process that is compatible with the rest of operations.

At the 101st AFS Casting Congress in Seattle last April, the AFS Cast Iron Div.'s Papers and Programs Committee (5-B) presented a panel with insight into the use, benefits and production of the alloy. Speakers from Ford Motor Co. and Chrysler Corp. discussed their use of exhaust manifolds and stressed how high Si-Mo improves performance. In addition, officials from Berlin and Crede-Liberty foundries discussed the production of the metal in their plants, detailing solutions to some of the common problems encountered.

FORD MOTOR CO.

Approximately 70% of the exhaust manifolds currently produced for Ford Motor Co. are high Si-Mo ductile iron. For most applications, the creep resistance of high Si-Mo gives sufficient durability to ensure an operating life of 10 years or 150,000 miles in a vehicle. In addition, the casting, raw materials and machining costs of high Si-Mo manifolds are lower than other candidate materials. However, the bottom line is cost. In terms of all the functional and material considerations, high Si-Mo ductile iron gives the best combination of properties with the lowest cost.

Design Considerations

The exhaust manifold plays a large part in meeting cost and performance targets. Within this framework, the design engineer must consider package size, operating temperature, flow characteristics and design configuration. Packaging considerations include package size, or the amount of space allotted to the exhaust manifold in the assembled engine, orientation of the engine in the engine compartment (longitudinal vs. transverse mounting) and the necessity of heat shields to protect other engine components. These items influence how air flows around the exhaust manifold, which in turn affects the maximum skin temperature of the manifold.

Next, operating temperature is determined mostly by calibration, or the factors like air-fuel ratios and fuel flow rates necessary to achieve the desired engine output and meet emissions standards. As standards become tighter, engines must run leaner to meet them, and running leaner means running hotter. Typical exhaust gas temperatures for Ford are 1600-1650°F (871-899°C), but manifold skin temperatures can be 150-250°F cooler, depending on how the engine is packaged.

Another issue is power. Engine power is all about air flow. The more air you can move into and out of the combustion chamber, the higher the power output for an engine. In exhaust manifold design, runner length, port size and the relative amount of air flow from each runner affect flow characteristics. Long runners of equal length, larger port sizes and balanced air flow among the runners are desirable.

The three basic configurations used in exhaust manifold design are individual runner, log style and bifurcated. Individual runner manifolds are made from stainless steel tubing. The log-style and bifurcated designs lend themselves more readily to casting alloys, like high Si-Mo ductile iron.

Some other functional considerations include thermal inertia, NVH, durability, weight and cost. The issue of thermal inertia involves how fast the catalytic converter can be brought up to operating temperature. Since the catalyst must reach about 500°F (260°C) before it starts to work, the ex-

<table>
<thead>
<tr>
<th>Material</th>
<th>Maximum Temperature (°F)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gray Iron</td>
<td>1000°F (540°C)</td>
</tr>
<tr>
<td>Compacted Graphite Iron</td>
<td>1200°F (650°C)</td>
</tr>
<tr>
<td>Ferritic Ductile Iron</td>
<td>1400°F (760°C)</td>
</tr>
<tr>
<td>High Si-Mo Ductile Iron</td>
<td>1800°F (980°C)</td>
</tr>
<tr>
<td>Ni-Resist Ductile Iron</td>
<td>1700°F (925°C)</td>
</tr>
<tr>
<td>Ferritic Stainless Steel</td>
<td>1750°F (955°C)</td>
</tr>
<tr>
<td>Austentic Stainless Steel</td>
<td>1825°F (1000°C)</td>
</tr>
</tbody>
</table>

Fig. 1. The addition of Si and Mo results in a significant increase in the maximum recommended temperature of high Si-Mo over a D4512-type ferritic ductile iron.
haust manifold should heat quickly enough that it doesn’t become a heat sink, delaying the start of catalyst function.

Thermal inertia is more an issue of manifold wall thickness achievable with a given material than of differences in thermal conductivity between candidate materials. Noise, vibration, and harshness issues for exhaust manifolds also are closely related to manifold wall thickness. High Si-Mo manifolds tend to have the greatest wall thickness with slightly better NVH performance than cast stainless steel or fabricated stainless steel tube assemblies.

Durability is associated with an exhaust manifold’s resistance to cracking during engine operation. A dynamometer test is run on the engine to evaluate manifold durability. During a rigorous cycling of the engine, temperature extremes are meant to induce cracking by thermal fatigue in the shortest amount of testing time. In general, materials with austenitic matrices are somewhat more durable than those with ferritic matrices.

As automakers strive to improve the fuel efficiency of their vehicles, component weight becomes more critical. In most cases, the significant differences between candidate materials for exhaust manifolds is not in their density, but in the wall sizes and their durability.

Tube fabrications are the lightest exhaust manifold designs. Stainless steel manifolds, cast using state-of-the-art thin wall processes, are heavier than tube fabrications but lighter than conventional high Si-Mo manifolds.

Finally, the maturity of casting processes and the relative cost of raw materials make high Si-Mo exhausts the cheapest of material alternatives. Cast stainless manifolds occupy the upper end of the cost scale, and tube fabrications fall somewhere in between.

### Material Properties

Based on functional considerations and knowledge of the manifold’s high-temperature environment, the following material properties are important production considerations:

- coefficients of thermal expansion and microstructure stability are both factors in determining the tendency of an exhaust manifold to grow, shrink or warp in service;
- thermal conductivity is somewhat related to thermal inertia, but wall thickness is a much more important consideration;
- resistance to thermal shock is important because the engine is by no means safe from rainwater or road spray;
- creep resistance is critical to durability, as the ability to endure cycling among the temperature extremes without yielding is essential to a manifold’s long-term function;
- corrosion and high-temperature oxidation resistance is necessary to maintain function throughout the manifold’s life. With the exception of Ni-Resist ductile irons, high Si-Mo ductile is the best of the cast irons for these thermal properties (Fig. 1).

### Consumer Expectations

In its suppliers, Ford looks for technical competence and a willingness to be proactive in the market.

Design engineers don’t have day-to-day exposure to foundry operation and don’t keep up with new foundry technologies, as suppliers should.

Foundries should employ state-of-the-art technologies in melting, molding, casting and quality control. They also should be familiar enough with the end use of the product that they realize the implications of changes that they make in their processes on the ultimate function of the part.

In addition, foundries should be proactive, looking for opportunities to improve product quality and lower cost. Be ready to show how these improvements will maintain, if not enhance, the end function of the part.

Component design and material selection are not independent of each other. The material tendencies are just that—tendencies. Designs can be modified to cover up the deficiencies of a given material. For example, adding ribs to support weaker sections can help a material survive at higher operating temperatures.

### CHRYSLER CORP.

A wide variety of available materials are used in exhaust manifolds, and high Si-Mo falls between ductile iron (D4512) and Ni-Resist in terms of durability and cost. In 1977 Chrysler Corp. began switching from gray to ductile iron manifolds because ductile iron manifolds are more durable in general purpose applications. In 1980, however, when Chrysler began dynamometer endurance testing the material in its prototype turbocharged engines, it found that standard ductile iron ran only 510 cycles (in a 600-cycle test schedule) before it cracked. The standard ductile iron manifold was distorted, which leads to exhaust gas leakage, and displayed heavy internal oxidation scale, which could damage the turbo unit. Based on the results of this test, the turbo engine program decided to switch to Si-Mo, which surpassed all performance objectives (Fig. 2). The first high-volume U.S. production application of high Si-Mo was Chrysler Corp.’s 1984 2.2L turbocharged Laser.

### Performance

The key performance elements of high Si-Mo ductile iron are its graphite nodules, ferritic microstructure and Si and Mo content.

First, the alloy’s graphite nodules are discrete spheres that inhibit rapid oxi-
dation. Gray iron has interconnected graphite flakes that rapidly diffuse oxygen, causing oxidation and distortion.

Next, high Si-Mo's ferritic microstructure has higher thermal conductivity than pearlite/austenite, which means lower thermal stress. Ferrite, unlike pearlite, experiences no growth (distortion) due to high temperature decomposition.

Finally, the material's Si content promotes ferritic phase stability at high temperatures and forms a thin protective surface oxide film that prohibits further oxidation. In addition, Mo promotes high-temperature strength and creep resistance.

**Cost**

Currently, high Si-Mo is slightly more expensive than standard ductile iron because of the additional work in alloying and its reduced casting yield, which is a result of its reduced feeding distance and its propensity for shrinkage. In addition, extra handling care is required because high Si-Mo is more brittle and prone to cracking.

**Machinability**

In comparison to standard ductile, high Si-Mo requires more time for machining. Conventional high-speed steel drills can be used for standard ductile, but carbide- or cobalt-tipped drills are used for high Si-Mo at 35% less speed. In milling, carbide cutters can be used for both materials, but the cutters have only 33% of the tool life at the same feed when used for high Si-Mo.

**Future Trends**

Chrysler currently has four engines that use high Si-Mo manifolds, and at least two additional applications are near term. The trend in today's vehicles is for tighter packaging and less cooling air flow around manifolds, which in turn will cause higher temperatures. The use of high Si-Mo will increase because of the possible emissions reductions, the increase in engine duty cycles (which means greater horsepower and torque from smaller displacement engines), its application in thinner-walled, lighter manifolds, its heat resistance and its relative low cost.

**GREDE-LIBERTY**

Grede Foundries' Liberty plant in Wauwatosa, Wisconsin, is a medium to short run jobbing shop with an annual casting production of 15,000 tons, including 85% ductile iron, 15% high Si-Mo, and less than 1% specialty alloy (D2, D5S Ni-Resist). Liberty has three 6-ton line frequency coreless melters, and molding is done with automatic and manual green sand and shell molding. Both coldbox and shell cores support the molding.

**Microstructure**

Similar to most ductile iron, the nodularity requirements are 80% minimum nodularity and 100 nodules per sq mm. The matrix of the iron is 90% Si-rich ferrite, with a grain boundary network of 5-10% primary carbidies and pearlite. Volumetric expansion may cause microcracks at grain boundaries, increasing the oxidation potential and reducing mechanical properties. The pearlite is not the typical lamellar structure but more like spherical carbide in a ferrite matrix at the grain boundaries. This is caused by C precipitation at grain boundaries due to the high Si in the matrix, which retards diffusion to the graphite. This rich C layer is precipitated as spherical carbides. A 5% maximum carbide specification is typical (Fig. 3).

Carbides are present due to alloy segregation. High Si content in the growing austenite rejects the carbide-stabilizing element, which in turn promotes high concentration in the liquid around the austenite grains. The liquid precipitates primary carbides at the grain boundaries.

**Mechanical Properties**

The typical mechanical properties of high Si-Mo are as follows: a tensile strength of 65,000-75,000 psi, a yield strength of 55,000-60,000 psi, elongation of 8-10% and a hardness of 187-255 Bhn (4,400-3,800 BID). These are similar to ferritic ductile iron, however the elongation is reduced by the embrittling effect on ferrite of high Si and the presence of pearlite/carbides at the grain boundaries. The greater hardness of the predominately ferritic structure is due to the higher-than-normal Si and the presence of grain boundary carbides.

**Production and Controls**

Liberty uses similar controls for producing high Si-Mo as it does for regular ductile iron. Steel scrap must be clean as well as low in carbide-stabilizing and pearlite-promoting elements. Returns are segregated by alloy type in an effort to keep contamination out of the melt. All charge materials must be accurately weighed and added consistently. Base iron is controlled by thermal and spectrographic analysis, and both lap temperature and holding times are monitored.

The iron is treated in a tundish ladle. Again, the accuracy of alloy weight, iron weight and fill time is important. Pouring is done with manual ladles, and post-inoculant is added to these ladles upon filling. The pouring start temperature is monitored. In-mold inoculant is widely used as the final inoculant step. Shakeout must provide an adequate amount of cooling time to promote the ferritic structure. Avoid heat treatment if not required by the customer.

**Production Concerns**

The production of high Si-Mo poses special concerns involving feeding, gating, flotation, machinability and chemistry analysis systems.

**Feeding:** Due to the lower C content there is less graphite present, hence there is less expansion to offset the liquid-to-solid volumetric contraction. The lower C and higher Si contents create a wide freezing range alloy, and dispersed porosity is common. More directional solidification is required to create soundness. This results in larger risers, more risers (due to the reduced feeding distances) and lower casting yields.

**Gating:** A high concentration of Si and low amount of C reduce fluidity, therefore requiring higher pouring temperatures and larger choke areas to fill faster. This alloy is prone to coldshuts and misruns.

**Flotation:** Requirements for high Si means lower C must be maintained to reduce the risk of hypereutectic composition and graphite flotation.

**Increased Slag Tendency:** The presence of high Si increases slag formation temperature, which in turn increases the chance that slag will form upon cooling.

**Machinability:** The presence of grain boundary carbides/pearlite increases tool wear. Due to the
hardening effect of Si on ferrite, the ability to remove metal is reduced.

**Inoculation:** A high nodule count is required because high Si reduces the diffusion rate of C in the austenite. A high nodule count reduces the distance between graphite centers, offsetting the reduced diffusion. A greater grain boundary area "produces" more finely dispersed carbides. High nodule counts also increase the fracture centers in the ferritic structure, thereby increasing machinability.

**Spectroscopy:** The strong graphitizing effect of Si makes it difficult to obtain graphite-free samples. This may contribute to erroneous analyses. The high heat resistance of this alloy requires higher burn temperatures, therefore argon purity must be high. Use of a purifier is recommended.

### BERLIN FOUNDRY

Berlin Foundry, a division of Citation Corp. in Berlin, Wisconsin, is a gray and ductile iron plant that was transformed from a captive operation to a jobbing shop in the late 1940s when it started producing small-dimension, air-cooled engine castings and the associated green sand attachment parts.

As the business expanded and customers increasingly demanded reduced costs, a gray cast iron horizontally-parted molding line with electric melting was built in the early 1970s. As the demand for ductile iron increased, a similar plant was built in the early 1980s to serve that market.

Currently, the foundry pours 4000-5000 tons of castings per month with a ratio of 60% gray and 40% ductile iron. High Si-Mo castings make up 6% of its ductile iron production. Cores at Berlin are made in a variety of ways, including the coldbox, nobake, shell and waxmold processes.

### Production Method

As Berlin started production of the high Si-Mo ductile, it needed to find a way to produce it by ladle addition. Its 14-ton ductile furnaces operated at 60 cycle units by charging to a heel. With an initially low percentage of high Si-Mo production due to the cost of the alloys, it was prohibitive to charge in the furnace.

Fortunately, the facility had a treatment ladle with a high height-to-diameter ratio, which was made by downsizing an 8000-lb hot metal carrier to make 1000-lb treatments.

The plant used 2.5% cover steel with regular practice, and management felt that the foundry could substitute the needed ferrosilicon (FeSi) and Mo for the cover steel. The initial production was made this way, and Berlin has continued the practice. This method provides another benefit in avoiding base iron transition problems. Only the base C is adjusted while the base Si is kept the same. Thus, the time and effort for conversion is kept to a minimum.

Berlin Foundry's standard high Si-Mo production method is as follows:

1. 1000 lb treatment;
2. base C of 3.3-3.45%;
3. base Si of 1.5-1.7%;
4. 24 lb of 75% FeSi;
5. 14 lb of magnesium (Mg) FeSi (5.75% Mg);
6. 11 lb of ferromolybdenum (FeMo);
7. tap at 2700-2800°F (1482-1538°C) (depending on section size);
8. add 7 lb FeSi on transfer to the pouring ladle;
9. pour at 2550-2650°F (1399-1454°C).

### Controls

Because there are several chemistry variations for high Si-Mo, Berlin has developed a common analysis and has established expected mechanical properties/hardness. The chemistry, matrix structure and mechanical properties are critical characteristics of high Si-Mo ductile iron and must be controlled (Fig. 4). Berlin's controls are as follows:

**Base Iron Chemistry and Tap Temperature:** Normal control will produce consistent final results.

**Treating Ladle Maintenance and Treating Practice:** The bottom of the ladle is the foundry's treatment pocket, and size control is required to get uniform recoveries.

**Pour Off Time and Nodularity Fade:** Normal nodularity control is required.

**Nodule Count and Primary Carbide Formation:** Nodule count must be maintained. Carbides are not usually a problem.

**Final Casting Chemistry:** The foundry performs final spectrographic audits and utilizes SPC not only to identify possible out-of-specification taps, but also to provide ongoing trend analysis.

**Matrix Structure:** A minimal amount of retained pearlite and a minimal grain boundary carbide network is required.

**Casting Soundness:** Isolated sections are found in castings, and periodic ultrasonic audits are performed.

### Problems

The thin sections of manifold castings and the temperature loss from treating may result in coldshuts and misruns, requiring attention to metal handling. Jobs must be gated to pour fast, and iron pourers must keep sprues full to avoid casting defects.

Another possible problem is microshrinkage. Microshrink will occur more often from below-specification pouring temperature as it affects the volumetric shrinkage and riser piping.

In addition, due to the high percentage of Si, it is difficult to obtain graphite-free chilled spectroscopic samples. Out-of-specification analysis from this testing can increase errors and other analyses to verify the chemistry for Si and Mo. Disciplined in sample pouring can avoid some of these problems.

---

For a free copy of this article circle No. 341 on the Reader Action Card.