SOLUTION STRENGTHENED FERRITIC DUCTILE CAST IRON PROPERTIES, PRODUCTION AND APPLICATION

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Abstract

The ductile cast iron standard in Europe also considers new ductile cast iron grades with a unique combination of tensile strength with high elongation (e.g. Rm 72520 psi with A_5 *14%) achieved by the solution strengthening of the ferritic matrix by silicon with contents between 3% and 4.3%. The new grades tolerate a higher amount of pearlite and carbide stabilizing elements without the generation of embrittling pearlite or carbides in the microstructure. The presence of Cr, Mn, and V do not influence the elongation significantly. An advantage of the new cast irons is the cost efficient machining due to lower tool wear. The tool life with the machining of the fully ferritic grades GJS-500-14 and GJS-600-10 is about 50–60% longer in comparison to the ferritic-pearlitic grades. The investigated grades show very good cyclic mechanical properties but lower dynamic properties. The pre-condition to achieve optimized properties by well-shaped graphite nodules, achievable with special inoculation techniques, adjusted to the high silicon content and the solidification rate, otherwise threaten graphite degenerations. There is no increased danger of dross generation or of a worsening flowability (investigated with special test equipment). Also the supposed inclination to the generation of porosities with the higher Si content was not confirmed.*

Keywords: *new silicon-alloyed ductile cast iron grades, ferrite, solution strengthened, tensile strength, elongation, hardness, machinability, DIN EN 1563, GJS, Germany, continuously cast products, rollers and pinion cages.*

Introduction

EN-GJS (European Standard for ductile cast iron) is used in many areas of mechanical engineering, automotive and engine construction as well as energy, environmental and nuclear technology. In all these applications, the EN-GJS grades must be in line with the applicable standards. When the DIN standard EN 1563 established in March 2012 was revised,[1] the ferritic, solution strengthened grades EN-GJS-450-18, EN-GJS-500-14 and EN-GJS-600-10 with higher Si contents were newly added to the standard. (DIN = Deutsches Institut fűr Normung, German Institute for Standardization) The values listed in Table 1 are valid for a nominal thickness ≤ 1.18 in. The conventional ferritic/pearlitic grades continue to be in the standard without any modifications. Due to the benefits associated with the new ferritic grades—namely higher yield strength and greater elongation, the number of applications is expected to increase quickly.

The mechanical properties of the ferritic/pearlitic EN-GJS grades under EN 1563 are set by adjusting the ferritic/pearlitic ratio through the addition of pearlite forming agents. These cast iron grades usually contain between 2.0% and 2.5% Si. Strongly varying wall thicknesses in EN-GJS-500 and EN-GJS-600 castings with pearlite contents of approximately 30%-70% may lead to strongly varying pearlite fractions and as a result significant differences in hardness. This makes it difficult to comply with close hardness tolerances. The unique combination of yield strength and tensile strength with high elongation in the new material grades

Table 1. New Material Grades in Standard DIN EN 1536
(Values in brackets are conventional ferritic/pearlitic grade properties)

Material	GJS-450-18	GJS-500-14	GJS-600-10
Tensile strength Rm [N/mm^2 / psi]	450 / 65268	500 / 72520	600 / 87024
Yield strength Rp0.2 [N/mm^2 / psi]	350 / 50764 (310 / 44962)	400 / 58016 (320 / 46413)	470 / 68169 (370 / 53665)
Elongation A_5 [%]	18 (10)	14 (7)	10 (3)

is achieved by solution strengthening of the ferrite matrix through higher silicon contents. To the user of the castings, these materials provide the advantages of better machinability, and uniform hardness and strength throughout the casting. At the same time, it provides the possibility of reducing the wall thicknesses (light-weight construction) with the intention of saving energy and raw materials. An important benefit for the foundries is that it becomes less difficult to comply with hardness tolerances.

When the new DIN EN 1563 standard became effective, very little knowledge was available as to the production and properties of the new ferritic, solution strengthened grades. The German and Austrian governments sponsored a research project which had the objective of filling this gap of material-related and casting technological information.

Experimental Procedure

Within the framework of this project, alloys were produced in a 150 kg induction furnace (medium frequency). The basic analysis of the alloys was C: 3.5-3.6 %; Si: 2.3-2.5%; Mn: 0.15-0.2 %; P: <0.02 %; S: <0.009 %; Mg: 0.04-0.05%. This basic analysis was used as reference to determine the effect of higher Si contents. During tundish cover treatment with FeSiMg, the pre-alloy was covered by very finely cut steel sheet. The tapping temperature from the induction furnace was set at 2,768°F-2,804°F, the casting temperature was between 2,516°F and 2,534°F. Inoculation took place in the pouring basin during casting. The melting tests were all conducted with the same basic charge–40% steel and 60% Sorel metal. The melting parameters were the same for all tests. The silicon contents were all set using FeSi 90, with the carbon content being adjusted by means of electrode graphite to a CE value of ~4.3. Except for specific inoculation tests, the amount of inoculants was 0.3% for all tests. The inoculants were added to the pouring stream of the magnesium-treated melt while it was being poured into the basin. The stoppers of the pouring basin were pulled upon reaching a casting temperature of 2,516°F-2,534°F. This made the casting temperature and the casting speed of all test melts comparable. A pattern from previous projects was used for casting radial specimens for the basic material-technological examinations. For this project, a 0.20-in.-thick plate was added to the radial pattern (Figure 1).[2] In addition to this radial specimen, technological test pieces were cast in a mould for standard specimens of the dimensions specified in DIN EN 1563 as well as Y2 and Y4-keel block. The two moulds were filled with metal from the same pouring basin in order to guarantee that the metallurgical preconditions are the same. Additionally, three shrinkage specimens were cast on the same mould plate. For complementary shrinkage tests, additional plate-, cylinder- and cube-type castings were produced (not in the figure shown). Tensile test pieces and metallographic sections were taken from the thermal center of the radial specimen. The results of the examinations were documented and evaluated.

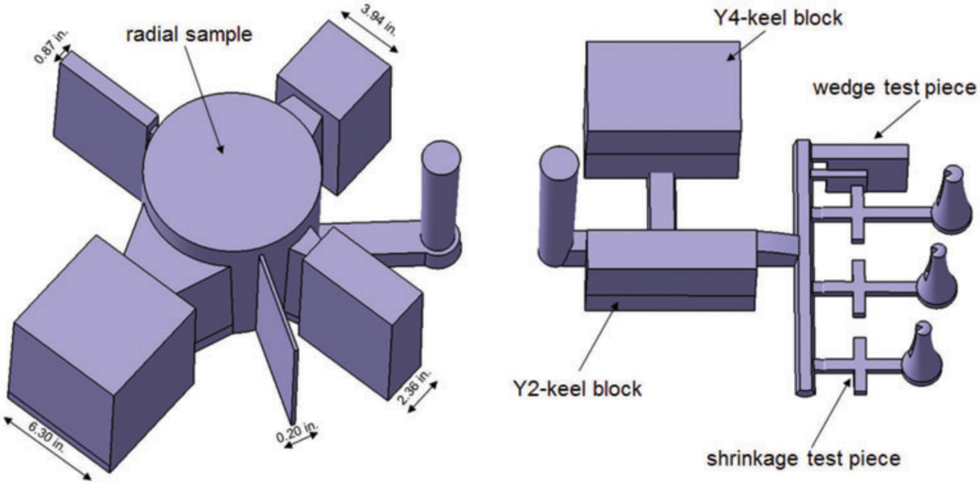

Figure 1. Geometry of the radial sample (left) and the Y-blocks and one type of the shrinkage test samples (right).

The fatigue tests were carried out under rotation bending conditions within minimum 15 samples (stress ratio R=-1). The test frequency was 200 Hz and the investigations were conducted at room temperature. The sample length and diameter were 6.30 in. and 0.28 in. respectively.

Test Results

Influence of the Si Content on the Static Mechanical Properties

Melting tests were conducted with Si contents between 2.4 and 6%. From the cast specimens, test bars were taken and tested. When the Si content is increased starting from 2.4%—which is the usual Si content in EN-GJS—the tensile strength values increase up to a maximum, which is reached at an Si content of 4.3%. After surpassing this Si content, the tensile strength drops from the peak of 89,000 psi down to 72,500 psi at a Si content of 5% (Figure 2). The yield strength only starts to drop at a Si content of about 4.6% (Figure 3), an effect known from ductile cast iron grades, such as EN-GJS-400-18. In these grades, growing generation of embrittling elements or graphite degeneration first lead to decreasing tensile strength and elongation, before the yield strength decreases due to further advancing embrittlement and graphite degeneration. At 5% Si, the yield strength and the tensile strength values coincide. In the tests, it appears that the drop is caused alone by the embrittling effect of the silicon. Degenerated graphite, which acts as internal notches, does not exist in the microstructure of the Y specimens. When the Si content exceeds 4.3%, elongation decreases together with the tensile strength. Above 5% Si, elongation is no longer measureable. Metallographic examinations have shown that the matrix is 100% ferritic within the complete alloying interval investigated. Embrittling phase components were not detectable by light or electron microscopy. The critical Si content, at which solution embrittlement starts, is between 4.2 and 4.4 Si.

Influence of Carbide and Pearlite Stabilizing Elements

Mn, Cr and V are the elements that are most likely to lead to pearlite and carbide formation in unalloyed or low-alloyed ductile cast iron. According to Reference 2, the static mechanical properties primarily depend on the pearlite content, while the dynamic mechanical properties mainly depend on the carbide content in the microstructure and decrease with increasing carbide content. Increasing Si contents promote the formation of carbide-free microstructures.[3]

Within the framework of the tests, the effect of significant contents of pearlite and carbide stabilizing elements was investigated on an exemplary basis. In these tests, alloys with compositions that were expected to cause carbide precipitations, i.e. max. 1.0% Mn, max. 0.6% Cr, max. 0.26% V and max. 0.17% Ti, were prepared and cast into Y2 specimens of 1 in. thickness and Y4 specimens of 3 in. thickness. Tensile bars and microsections were taken from these specimens. In Figure 4, the static mechanical properties determined in the alloying tests are plotted against the properties of the unalloyed material. The alloys with the individual elements changed within the investigated content range and cast into separate specimens did not show any significant influence on the mechanical properties compared to the unalloyed specimens, with the exception of chromium. With a Cr content of 0.6%, the elongations are 10% and 14%. This is lower than the value of unalloyed melts, but still in compliance with the values specified for EN-GJS-600-10 in DIN EN 1563. The metallographic examinations showed that within the investigated alloying ranges carbide precipitation was found in none of the specimens. Figure 5 shows the microstructure of an alloy containing 1% of Mn. The matrix consists of 100% ferrite. The matrix of the alloy with a Cr content of 0.63% contains approximately 25% pearlite, but no precipitated carbide.

Influence of the Inoculation and Si Content on the Graphite Shape

The mechanical properties of ductile cast iron do not only depend on the structure of the metallic matrix, but also on the graphite form. Inoculation tests were conducted with the mould arrangement shown in Figure 1. All tests were

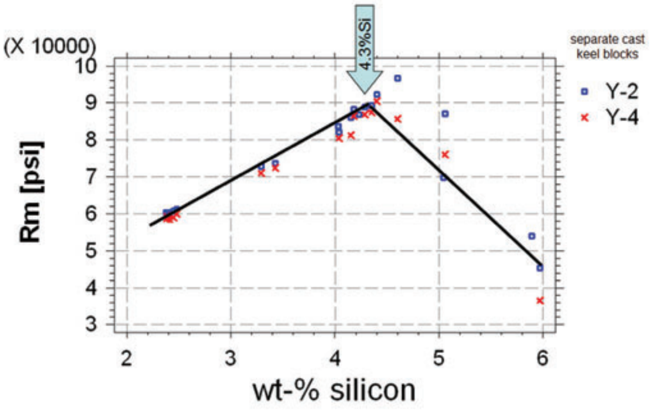

Figure 2. Tensile strength pass through a maximum in dependence on the Si content.

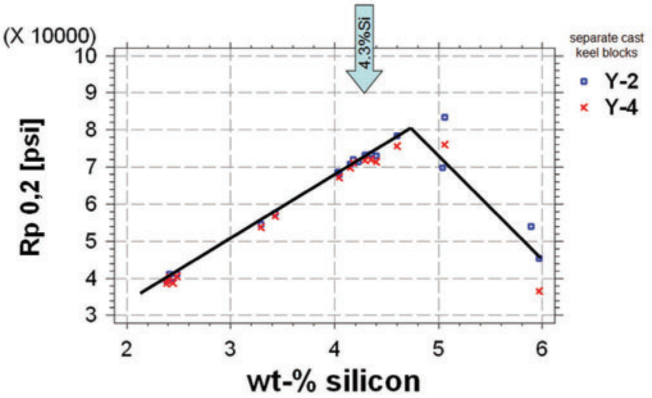

Figure 3. The maximum yield strength is at a higher Si content in comparison to the tensile strength.

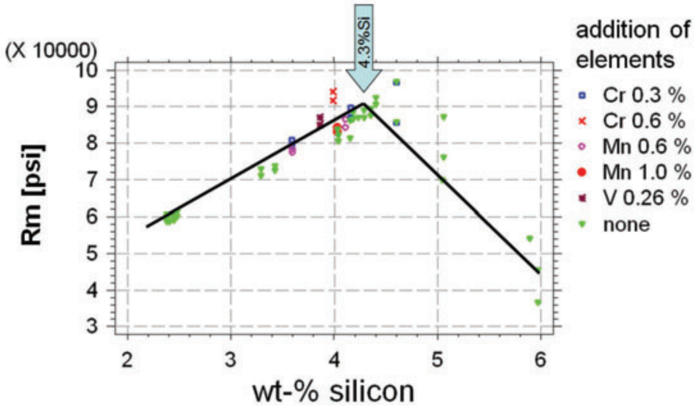

Figure 4. This graph shows no influence of the added elements on the tensile strength.

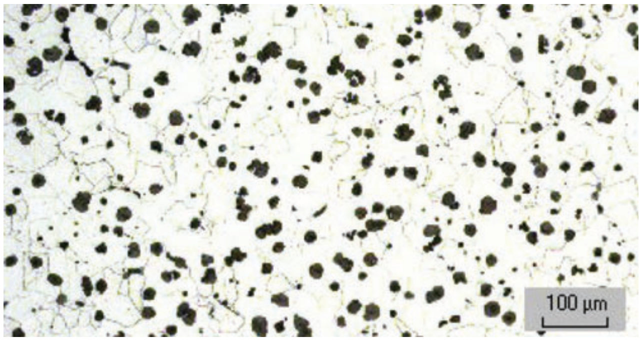

Figure 5. Microstructure of a material with 4.03% Si; 3.01 %C; 1.0 % Mn without pearlite (Y2-block).

made with the same inoculant content of 0.3%. A total of 12 different inoculants or blends of inoculants were used (FeSi basis with different fractions of Ca, Cer, Sr, Bi etc.). Figure 6 shows an example of examinations of graphite forms in samples taken from different areas of the radial specimen. The results are for one Bi-containing inoculant of the test series. Plotted in the graph are the sums of graphite shapes V and VI relative to the wall thickness and the Si content. (The graphite shapes were determined through image analysis according to DIN EN ISO 945-1.) It is evident that with a certain type of inoculant, the percentage of the sum of graphite shapes V and VI decreases with increasing wall thickness. An important finding is that with increasing Si content the graphite shape deteriorates. This trend was even more pronounced with other inoculants. In the 0.2-in. plate, the sum of the graphite shapes V and VI scatters between 80% and 100% with all inoculants used. Only the alloy without inoculants features 70% of graphite nodules of types V and VI. In the 6.3-in. wall, the scatter band is much wider, ranging from 35% to 90%. The broader scatter band can be explained by the dependence of the graphite shape on the Si content and the chemical composition of the inoculant.

In Si-alloyed GJS materials, the graphite may deviate from the shapes V and VI depending on the solidification rate (wall thickness) and the inoculation condition. These deviations may have a negative influence on the mechanical properties of the casting. They look in appearance macroscopically similar to chunky graphite. Figure 7 shows such degenerated graphite assembly which has been isolated through deep etching. An appropriate inoculation technique and the use of inoculant Bi help avoid such deviating graphite shapes.

Investigation of the Machinability

Thanks to the uniform hardness of the metallic matrix, tool wear is much lower with ferritic ductile cast iron than with the ferritic/pearlitic alloy EN-GJS-500-7. According to Reference 4, machinability is better by 10%.

To evaluate the machinability within the framework of this project, four of the investigated alloys were cast into cylinders of 4.73 in. diameter and 11.82 in. length. The tool life was used as a measure for the machinability of the four investigated cast iron materials. According to standard DIN 6583, the tool service life is the period elapsing until a certain wear criterion is reached under identical machining conditions. In the tests described here, tool service life was determined to be the time elapsing until a flank wear of 0.008 in. was reached.

The results show that the Si-alloyed, solution strengthened materials with a ferritic matrix can be better machined than the ferritic/pearlitic materials. The ferritic materials prolong the tool lives by approximately 50% to 60% (Figure 8).

Cast Techonological Properties of the High Silicon Ductile Iron

The high Si content of solution strengthened ductile cast irons is expected from previous experiences reported in the

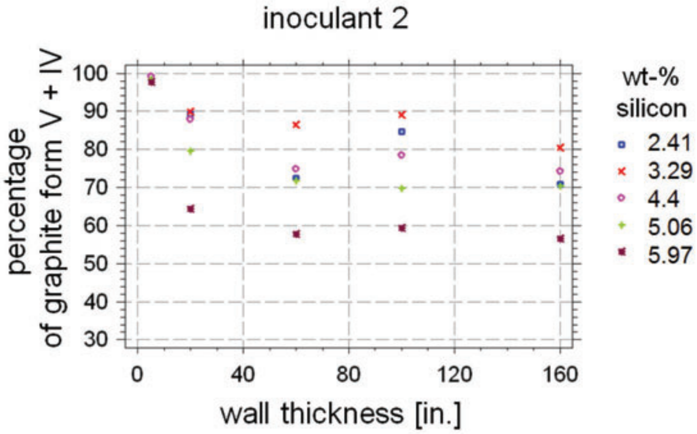

Figure 6. This graph illustrates that inoculant, Si content and wall thickness all affect the microstructure.

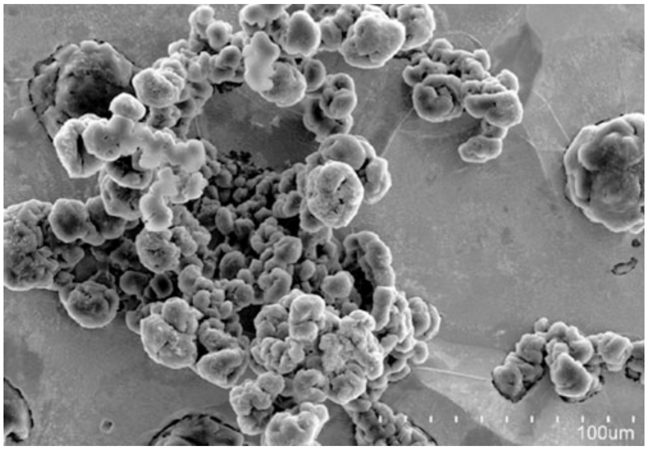

Figure 7. Graphite shape deviation comparable to chunky graphite.

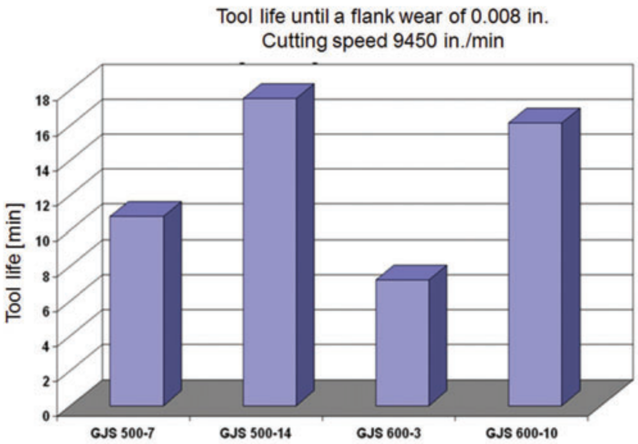

Figure 8. Tool life at cutting speed of 9,450 in./min with the machining of the grades EN-GJS-500-7, EN-GJS-500-14, EN-GJS-600-3 and EN-GJS-600-10.

foundries to lead to casting technological properties different from those known from conventional materials. Therefore several tests were conducted to examine the material's susceptibility to dross formation, its mould filling behaviour and shrinkage tendency.

In a dross test, the surface of the metal bath was exposed to oxygen (air) for 1 to 1.5 minutes in a basin. The complete melt including the dross layer was then poured through a filter, as illustrated in Figure 9. The pouring capacity was logged by means of a digital scale. Reproducible results of these tests were that cast iron with an Si content of 2.5% led to blocking of the filter, while with 4% Si in the cast iron the filter remained open (Figure 10). Hence, the result is contrary to what was originally expected, namely that a higher Si content would promote dross formation.

Further tests were conducted with a test casting specially developed for these materials (a casting harp with plates and webs of different thicknesses between 0.12 and 0.24 in.). The filling behaviour of the alloys in the "casting harp" was independent of the Si content. The differences if any resulted primarily from variations in the casting temperature.

Additionally, different plates, cubes and cylinders were cast using alloys with different Si contents (CE value was 4.3 in all cases). From sections taken from the feeders and feeder necks it could be told that the feeding requirement and extraction behaviour of Si-alloyed ferritic grades are virtually the same as with conventional cast iron grades. The comparison of the exothermal top feeders of, for example, different cast cylinders (height and diameter each 4.7 in.) with 2.2 and 4.0% Si showed no significant differences in the feeder weight and the appearance of the sections and the cut surfaces of the feeders. The evaluation of the feeder neck samples (cubes with edge length of 1.58 in. and at the side, arranged different dimension feeder necks)[5] showed on the other hand that it might be necessary to design the feeder neck somewhat larger when feeding alloys with higher Si contents under pressure.

Dynamic and Cyclic Mechanical Properties

Charpy impact tests were performed at temperatures between -94°F and 248°F with different conventional and solution strengthened ductile cast iron grades. As expected, the impact resistance of the solution strengthened grades was lower than that of the conventional grades (e.g. GJS-500-7: 7 J and GJS-500-14: 3 J at 77°F). Even at a test temperature of 248°F, the specimens of GJS-500-14 and 600-10 did not exhibit a clearly identifiable upper shelf.

In terms of the cyclic properties, solution strengthened ductile cast iron performs better. Figures 11 and 12 show the fatigue strength values of conventional ferritic/pearlitic GJS-500-7 and of ferritic solution strengthened GJS-500-14 in stress-cycle diagrams. At 40,624 psi, the fatigue strength of the solution strengthened ductile cast iron is higher than that of the ferritic/pearlitic material (37,235 psi).

Summary

Due to the favourable properties of Si-alloyed ductile cast iron grades (high strength at fairly good elongation, uniform hardness distribution and better machinability), a strong demand for these grades can be expected for the future. In Germany, this new group of material grades is already being used in various applications, e.g. continuously cast products, rollers and pinion cages.

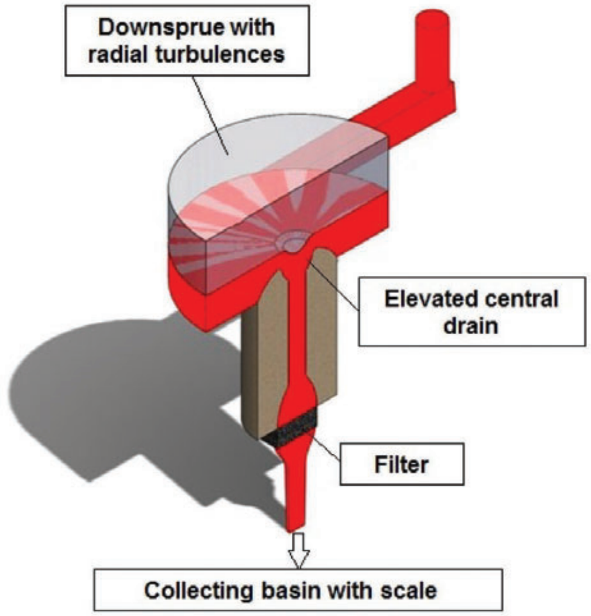

Figure 9. Testing device for the measurement of the dross generating behaviour of cast iron melts.

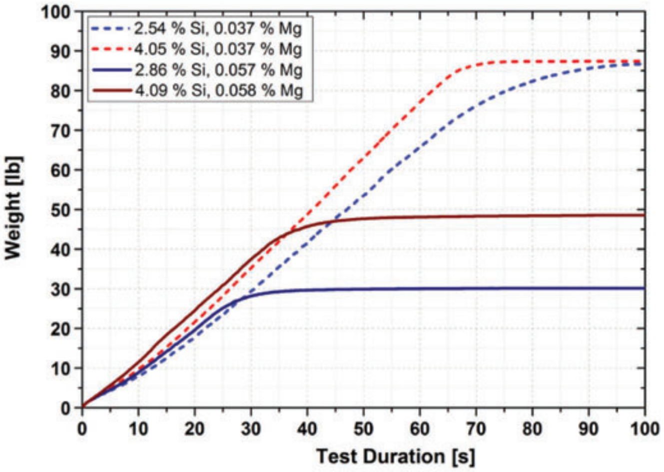

Figure 10. This graph illustrates weight versus test duration for basin filling with varied Si and Mg contents.

Silicon acts as ferrite forming agent. It increases the strength and hardness through a solution strengthening effect, generating a ferritic matrix with tensile strengths comparable with those of ferritic/pearlitic grades. Once the Si content exceeds 4.3%, the tensile and yield strength values decrease markedly.

Material grades solution strengthened through the addition of Si provide the potential of using lower cost, low-alloyed scraps in the metallic charge, without the risk of pearlite or carbide formation in the microstructure. For example, Mn contents up to approximately 1% and Cr contents of a few tenths of a percent are tolerable. In a particular case of application, a foundry reported material cost savings by 5% through the use of the new material.

Optimal graphite shapes and hence optimal mechanical properties can only be achieved with inoculation techniques properly adapted to the higher Si content and the maximum solidification time. Especially the Bi-containing inoculants have proved successful here. For solution strengthened ductile cast iron grades it is more important that an appropriate inoculation technique is chosen, because the high Si content may cause deviating graphite shapes.

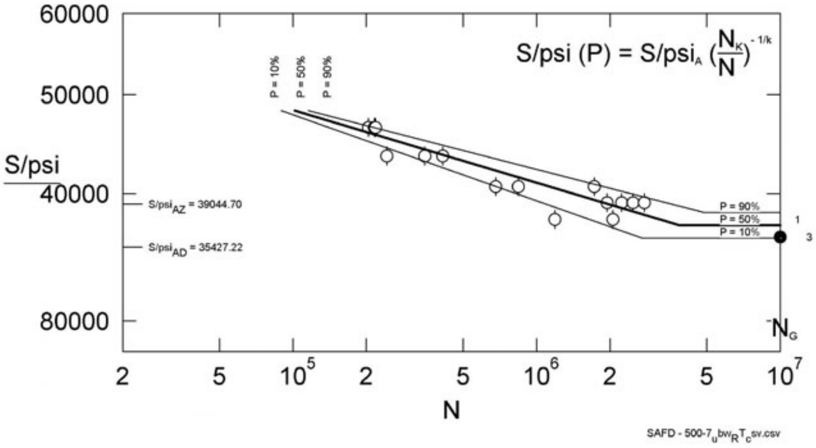

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Figure 11. Stress-cycle-diagram of the ferritic/pearlitic material GJS-500-7; fatigue strength: 37235 psi (P=50%).

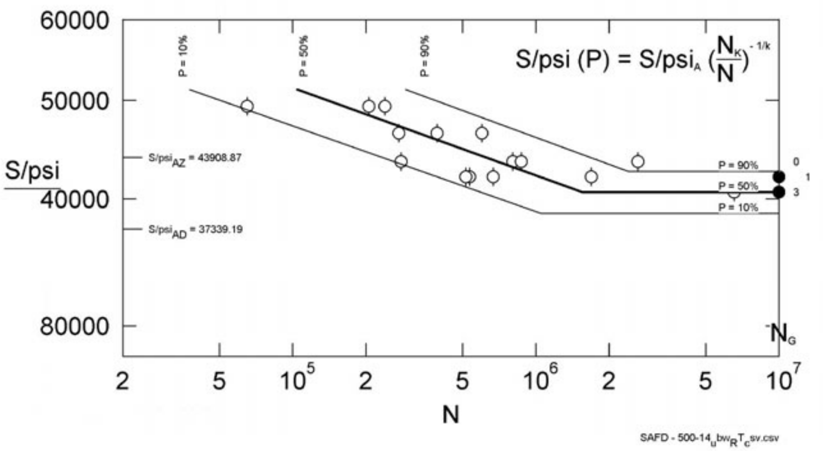

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Figure 12. Stress-cycle-diagramm of the ferritic material GJS-500-14; fatigue strength: 40624 psi (P=50%).

The production of castings can be optimized in terms of material properties as well as production and machining costs. Optimization means making use of the more favourable mechanical properties either in the form of small wall thicknesses (light weight construction) or higher loadability of the castings without the need to change the geometry. The up to 20% higher yield strength allows the wall thicknesses to be designed accordingly smaller. Moreover, machining the solution strengthened materials is less costly because tool wear is lower.

Casting properties, especially the susceptibility to porosity, do not change with increasing Si content. Existing pattern and feeding systems used for conventional casting alloys may not need to be modified for the new materials.

From the casting technological tests it can be concluded that the new grades show low risk of increased dross formation. Especially at room temperature and slightly elevated temperatures, the investigated new ductile iron grades exhibit good cyclic properties as a result of the completely ferritic matrix. All these aspects give these new materials a very high potential for future application in automotive engineering.

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