SSFDI – A potential alternative for lightweight design

Light-weight designs are central to improving efficiency and optimising energy consumption. In this quest for weight reduction and improved fuel economy cast iron has been and is still being replaced by aluminium in automotive application. Solution strengthened ferritic ductile iron (SSFDI) presents an interesting potential for reducing weight through its combination of higher strength and elongation. While being developed to provide better machinability properties of solution strengthened ferritic ductile iron, the material is now being recognised as having interesting potential to reduce weight. This potential is not only being recognised by the automotive but also the wind energy industry

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Introduction to SSF

In 2011, the second group of spheroidal graphite cast irons were included in the European standard EN-1563; solid solution strengthened ferritic ductile (SSF) iron. These grades were initially studied by Volvo in the early 1980s with the purpose of providing a material that provides similar mechanical properties as ferritic-pearlitic ductile iron grade EN-GJS-500-7 but was easier to machine. This work was presented at the World Foundry Congress in 2000 by LE Bjørkegren and K Hamberg and demonstrated that alloying with silicon provided a material with similar strength combined with higher elongation and lower and more uniform hardness to EN-GJS-500-7.

The incorporation of these grades in the European standard evoked renewed interest in SSF. In particular, German researcher H Löblich saw a need for investing in learning more about this material. He studied how to produce this material, the effect of carbide promoting elements as well as effect of silicon on static and cyclic mechanical properties at different temperatures. SSF exhibits a single matrix and a more uniform hardness independent of section size. This provides a solution to the known challenge of the ferritic-pearlitic grades and provides higher strength and elongation. This combination of property improvements creates new possibilities for other applications. Ductile iron grades have standardised names that indicate the tensile strength and elongation (in MPa and percentage, respectively) of a tensile test specimen, e.g. EN-GJS-600-10. It should be noted that these values are given for separately cast samples with relatively thin-wall (thickness below 30 mm). The requirements decrease as the wall thickness increases and these requirements for SSF grades of ductile iron from EN standard 1563 are shown in **Table1**. Requirements for mechanical properties also change if the tensile specimen is taken from the actual casting and these mechanical requirements are shown in **Table2**. For example, a tensile test bar taken from a casting with relevant wall thickness of 50 mm made from EN-GJS-600-10 only needs to have tensile strength of 560 MPa and elongation of 6% to meet the standard.

Compared to the ferritic-pearlitic grades the SSF grades provide higher elongation and yield strength at the same tensile strength as can be seen in **Table3**.

This combination of higher yield strength with higher elongation allows for lighter designs as the casting section thickness can be reduced. Expensive alloying elements also offer a more cost-efficient alternative.

This potential for light weight designs offers an interesting potential within the engineering segment. In addition, this material promotes maintaining cast iron and converting steel components within the wind energy segment.

Market review for SSF

Considering the growing interest in SSF, it is worthwhile to evaluate the market

Table1: Mechanical properties of SSF ductile irons according to EN 1563. Separately cast samples

Material	Relevant wall thickness t mm	0.2% proof strength Rp0.2 MPa	Tensile strength Rm MPa	Elongation A %
EN-GJS-450-18	t≤30	350	450	18
	30≤t≤60	340	430	14
	t>	To be agreed upon between manufacturer and purchaser		
EN-GJS-500-14	t≤30	400	500	14
	30≤t≤60	390	480	12
	t>			
EN- GJS-600-10	t≤30	470	600	10
	30≤t≤60	450	580	8
	t>	To be agreed upon between manufacturer and purchaser		

Source: ISO EN 1563 (2018), Founding – Spheroidal Graphite Cast Irons

Table2: Mechanical properties of SSF ductile irons from EN 1563. Samples cut from castings

Material	Relevant wall thickness t mm	0.2% proof strength Rp0.2 MPa	Tensile strength Rm MPa	Elongation A %
EN-GJS-450-18	t≤30	350	440	16
	30≤t≤60	340	420	12
	t>	Guidance value to be provided by manufacturer		
EN-GJS-500-14	t≤30	400	480	12
	30≤t≤60	390	460	10
	t>	Guidance value to be provided by manufacturer		
EN-GJS-600-10	t≤30	450	580	8
	30≤t≤60	430	560	6
	t>	Guidance value to be provided by manufacturer		

Source: ISO EN 1563 (2018), Founding – Spheroidal Graphite Cast Irons

Table3: Mechanical properties of SSF grades compared to ferritic-pearlitic in 30 mm tensile bar

	SSF	DI	SSF	DI	SSF	DI
Material Grade EN-GJS	450-18	500-7	500-14	700-2	600-10	800-2
0.2% proof strength MPa	350	320	400	420	470	480
Tensile strength MPa	450	500	500	700	600	800
Elongation A %	18	7	14	2	10	2
Hardness HB	170-200	170-230	185-215	225-305	200-230	245-335
Fracture toughness, KIC MPa√m	30*	22-25*	28	23*	15*	14*
Density kg/dm3	7.1	7.1	7.0	7.2	7.0	7.2

*Note: *K Vollrath, Neue, hochinteressante Kugelgraphit-Gusswerkstoffe, Giesserei, 09-2013* potential for this material. Modern Castings 51st Census of World Casting Production indicated the total annual production of ductile iron to be 25,467,378 tonnes in 2016. The potential for SSF is connected to converting ferritic-pearlitic castings, replacing ferritic castings within the wind energy segment and replacing steel castings and weldments.

When it comes to the wind energy segment, this is based on installed capacity estimated to be around 3 million tonnes of ductile iron per year. It should be possible to convert 30% or 900,000 tonnes; of this, however, around 90,000 tonnes are currently produced in SSF. This puts the total current production of SSF to 340,000 tonnes and which is about 1.4% of the total ductile iron production worldwide. However, this volume is increasing as more wind generator manufacturers see the benefit of using a higher strength ductile iron allowing for a weight reduction of approximately 30%.

With regard to the automotive sector, the OEMs are now starting to take notice of the new SSF grades and several foundries in India and China are now starting to run trials with the new grades. It is likely that within the next few years the market for these SSF grades will increase by around 20% of the current ductile iron automotive market.

Design of experiments

With incorporation of SSF in the European standard and increasing industry and academia interest in SSF, Elkem recognised the strategic importance of this material. Research on understanding how the treatment process and choices related to the treatment process affected the microstructure and properties was justified.

It was observed that significant regional differences existed for the preferred combination of MgFeSi and inoculation related to SSF. To understand better what combinations are favourable and whether some combinations are better than others it was decided to run a series of trials. (**Table4**)

The goal of each trial was to make EN-GJS-600-10 and achieve above minimum requirements for elongation, yield strength and ultimate tensile strength combined with a nodule density of more than 100 N/mm^2 and more than 80% nodularity. This grade is the most challenging SSF grade to achieve.

The four 1500-kg melts were prepared in a coreless-induction furnace from steel scrap. The actual final iron composition is shown in **Table5**.

The treatment was carried out in a tundish ladle with a pocket design that allowed a 20-mm cover layer to be placed on top of the MgFeSi. Addition rate of MgFeSi varied between 1.05 and 1.37% by weight of Mg to achieve the same target residual Mg content in the treatment ladle after deslagging. The treated iron was then divided into five 32-kg capacity pouring ladles at 30-second intervals where the inoculant had been added to the bottom. The inoculated iron was held for 1 minute prior to casting into a sand mould. The same inoculant was used in the first and last pouring ladle.

The type of sand mould varied from the EN 1563 separately cast option 3 round bar-shaped sample. Type 'a' only standard tensile bars were used in the first trial. The tensile mould, based on Norsk Standard NS-EN 1583:2001, is shown in **Figure1**, while the module used to evaluate the shrinkage tendency is shown in **Figure2**.

For each of the pouring ladles, a coin sample for chemical composition was collected using an immersion sampler

Table4: Description of three trials

	Trial 1	Trial 2	Trial 3
MgFeSi	A, B, C, D	A, B, E	A, E
Inoculant	1, 2, 3, 4, 5, 6, 7, 8, 9	1, 2, 3, 4	1, 3, 4
Cover	Steel	Steel + Specialty FeSi	Steel + Specialty FeSi
Mould	Type 'a' test bar standard tensile mould	Type 'a' test bar standard tensile mould + shrinkage mould	Type 'a' test bar standard tensile mould + shrinkage mould
Purpose	Find the best and worst treatment solution	Verify results from first trial and study effect of cover	Verify results of two previous trials and focus on inoculation addition

Table5: Actual final iron composition

Element	Trial 1	Trial 2	Trial 3
%C	2.6-2.9	2.9-3.1	2.8-3.1
%Si	4.4-4.5	4.1-4.3	4.3-4.4
%S	0.008±0.005		
%Mg	0.035-0.045		
Other	Max 0.35%Mn Max 0.03% P Max 0.01% Ti		

and four thermal-analysis-cups were poured. The chemical composition was determined as follows: C and S using a combustion technique, Si using wet chemical determination and all other elements using an Optical Emission Spectrometer.

The following parameters were used to evaluate the trials: chemical composition of the base iron, treated and inoculated iron, thermal analysis data of base iron, microstructure and mechanical properties of the final iron. A section taken was used for microstructure characterisation and both tensile bars were pulled to obtain tensile strength (Rm), yield strength (Rp0.2) and elongation (A5).

Microstructure and the characterisation quantification were carried out with a Zeiss optical microscope equipped using an Axioplan 2 automatic stage controller at a magnification of 100X. The digital camera provided an image resolution of 0.68 µm/pixel (1.47 pixel/µm), and an image size of 1280x960 pixels. For samples having chunky graphite the structure was only documented with a single photo at 100X.

Results

From the obtained results the following observation could be made:

Matrix is controlling the strength

Silicon is the element that provides the increase in strength as seen from **Figure3**. According to this figure, an Si level of 4.35% would be needed to achieve the target tensile strength of 600 MPa. This is higher than the indicated turning point in the work by Stets and shows in this case that the tensile strength continues to increase upto at least, 4.5% which was the limit of these trials. Each point in the curve is the average result of two pulled tensile bars.

Similar development is seen for the yield strength, while no clear trend is observed for the elongation.

A complicating factor associated with

Figure 1: Tensile mould used in the trials

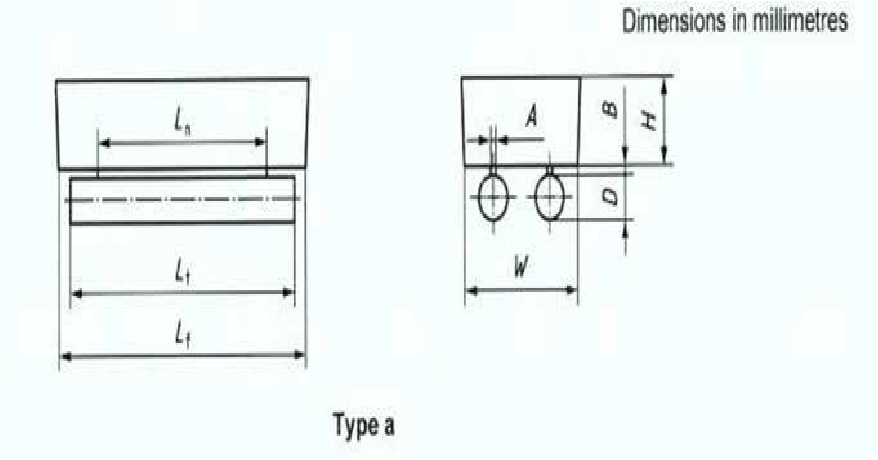


Figure2: Shrink module used for evaluation of shrinkage tendency. The arrow points at the section used to evaluate shrinkage tendency

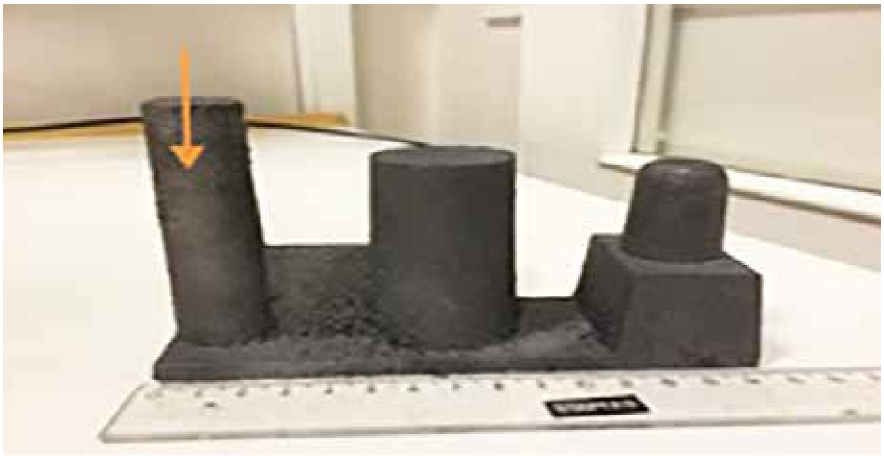


Figure 3: Tensile strength in relation to Si-content

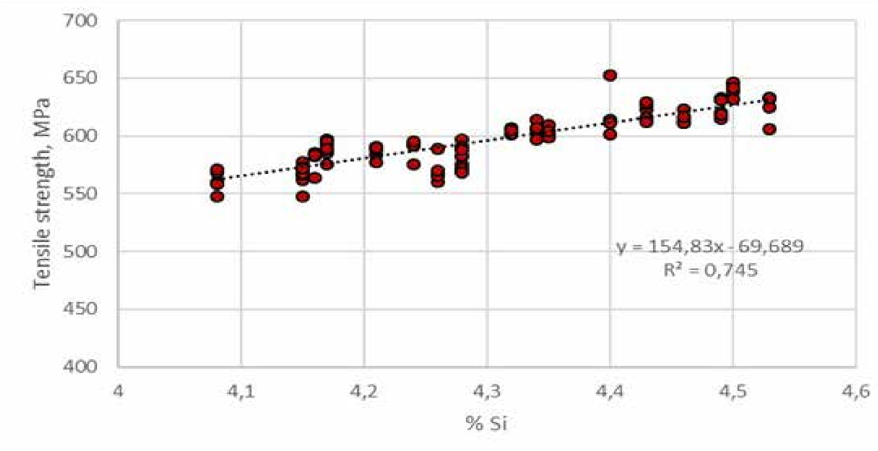


Figure4: Effect of nodule density on elongation

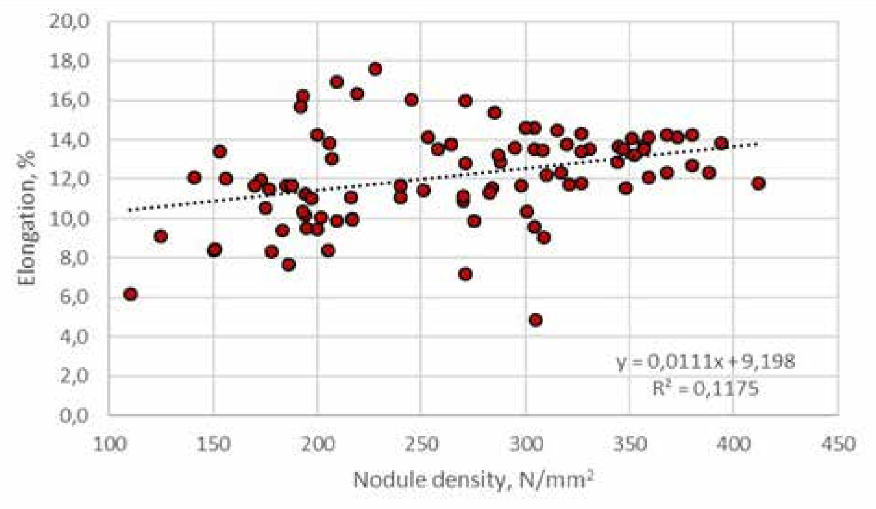
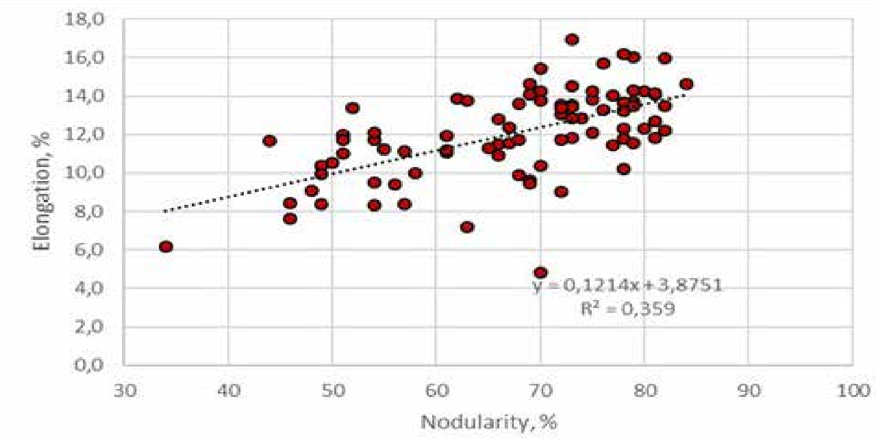


Figure5: Effect of nodularity on elongation



Si and the fact that the strength is so strongly connected to the Si-level is the increasing analytical error with increasing Si and lack of available certified reference material (CRM) and reference material calibration standards for SSF iron. It is therefore important to work with alloys with defined and consistent chemistry and sizing.

Graphite structure affects elongation

While matrix is controlling strength the graphite structure affects the elongation as can be seen in **Figures 4** and **5**.

As can be seen in Figures 4 and 5 the elongation increases with increasing nodule density and nodularity. From the figures it would also appear that nodularity is more important than nodule density; however, a high nodule density is often associated with high nodularity. An interesting observation is that a nodularity as low as 50% is sufficient to obtain the required minimum elongation of 10%.

The ISO standard EN1563 recognises that SSF is more prone to degenerated graphite as it approaches hypereutectic composition to obtain the required strength combined with best castability and lowest shrinkage tendency. As with regular ductile iron, it is important to optimize the C and Si levels in SSF iron to obtain the desired microstructure, mechanical properties, and castability. In **Figure6** difference in shrinkage tendency observed in the shrinkage module is presented for different amount of graphite and carbon equivalent.

In **Figure7** examples of varying graphite structure together with the respective elongation values are shown and as can be seen nodularity as low as 50% still provides elongation values above 10%. For samples where chunky graphite was observed in the structure the nodularity was set to 0%. An example of such a structure can be seen to the left in Figure 7 and as can be seen the elongation is only marginally lower than 10%. This suggests that SSF, due to its strong matrix, tolerate more degenerated or poorly shaped graphite.

Effect of treatment solution

Purpose of the trials was to learn how choices related to the treatment process affect the mechanical properties and the graphite structure. In the 3 trials, 21 MgFeSi treatments with 5 different MgFeSi compositions were conducted testing out 9 different inoculants, 2 cover materials, and 2 inoculant addition rates with and without Sb.

The main learning from the trials was that the choice of MgFeSi and cover was more important than choice of inoculants and the treatment choices mainly affected the graphite structure and to a lower extent the mechanical properties.

MgFeSi

Elkem's market survey showed there to be different regional preferences related to the choice of MgFeSi and specifically related to magnesium and rare earth level. In the trial, MgFeSi grades representing the regional differences were selected. These were studied to determine if there was any significant difference in effect between them on the final structure and mechanical properties.

Figure 6: Effect of carbon on account of graphite and shrinkage tendency at same nodularity, 80%

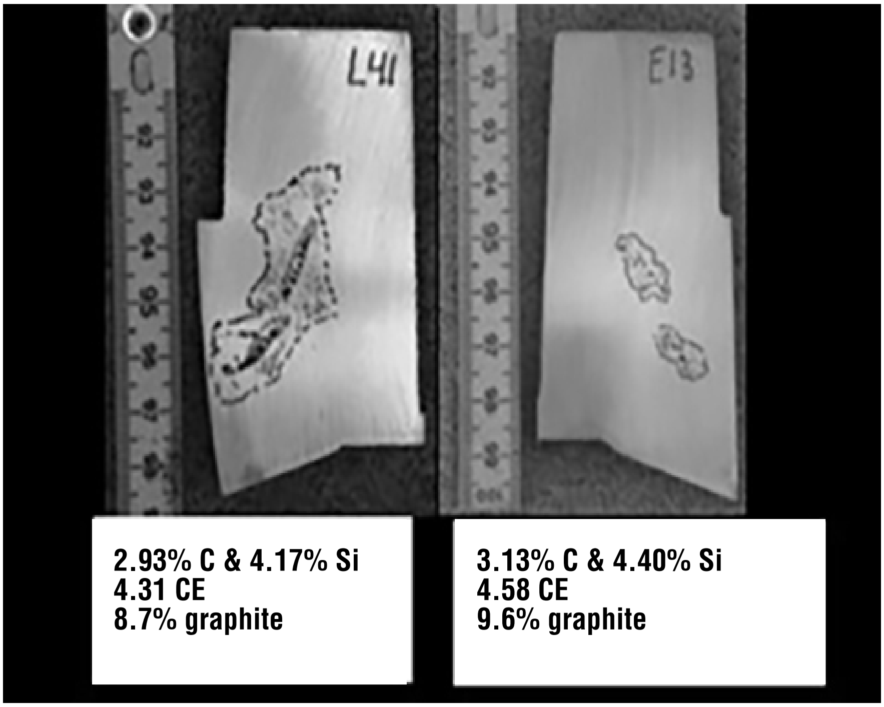
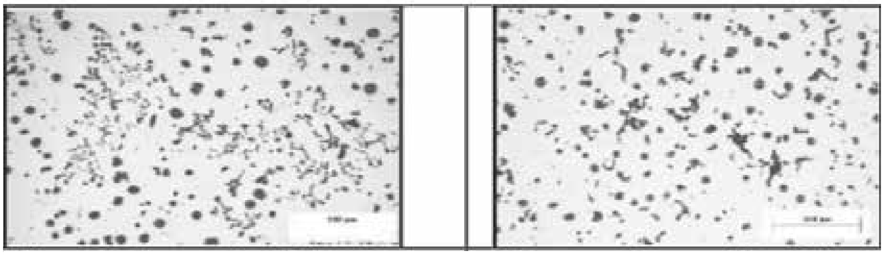
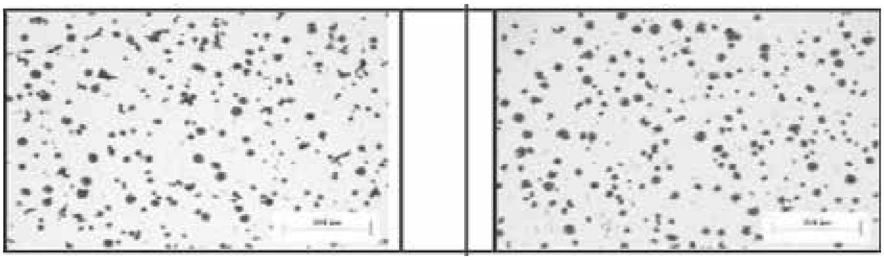


Figure7: Examples of SSF iron microstructures with corresponding elongation values



Elongation: 9,1%
Nodularity: 0%

Elongation: 10,4%
Nodularity: 49%



Elongation: 13,9%
Nodularity: 63%

Elongation: 16%
Nodularity: 84%

Examination of the thermal analysis data gave the first indication that choice of MgFeSi greatly affected the lower eutectic temperature which is often used as measurement for nucleation potential. This can be seen in **Figure8**.

As can be seen in Figure 8, MgFeSi A and E show a higher lower eutectic temperature than MgFeSi B, C and D.

This lower eutectic temperature value is from sample taken from treated but uninoculated iron.

In **Figure9** the difference in structure of MgFeSi A and D is presented after inoculation with the same inoculant.

Cover

Cover material is often used to delay reaction between MgFeSi alloy liquid iron while the ladle is being filled by allowing more liquid metal above the alloy before the reaction starts. Composition and size of the cover material vary from foundry to foundry and can be anything from steel chips, cast iron plates, FeSi to sand. In these trials dry steel punchings with a defined size was compared with specialty FeSi alloy with defined composition and size. Measures were taken to maintain same Si-level regardless of cover material.

In **Figure10**, the difference in graphite structure and nodularity is seen for steel and specialty FeSi cover material for same MgFeSi and subsequent inoculation.

Inoculant

Several different inoculants were tested in combination with different iron compositions and MgFeSi alloys. The types of inoculants tested were Sr, Ca+Ba, Ca+Al, Ca+Ce and Ca+Ce+Bi containing inoculants.

Antimony and Bismuth

Antimony (Sb) and Bismuth (Bi) are often recommended to counteract chunky graphite and to increase nodule density. In SSF the use of Bi+RE inoculants have been reported to be very successful in controlling chunky graphite. In these tri-

Figure8: Difference in lower eutectic temperature observed with different MgFeSi qualities

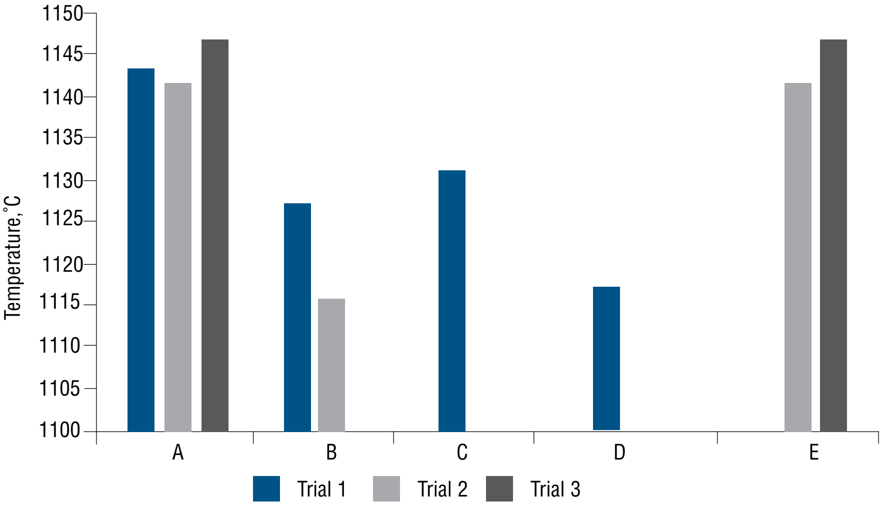
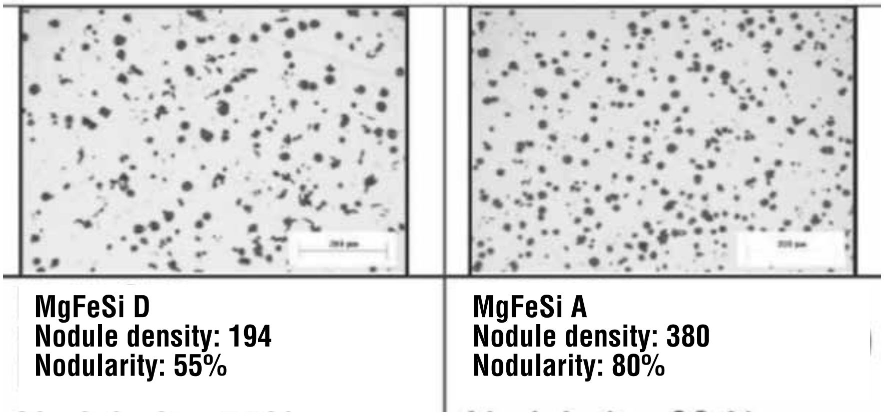


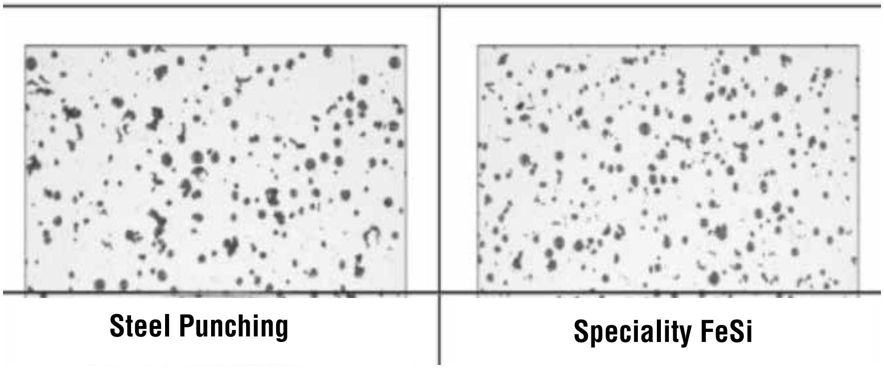
Figure9: Example of difference in structure with different MgFeSi alloys but using same inoculants



MgFeSi D
Nodule density: 194
Nodularity: 55%

MgFeSi A
Nodule density: 380
Nodularity: 80%

Figure 10: Example of difference in structure with different cover material but using same inoculants



Steel Punching

Speciality FeSi

als both Sb and Bi were tested to find out whether any of these elements had any significant effect in the graphite structure. To test out the effect of Bi a Bi+RE inoculant was used while to test out Sb a separate Sb addition of 20 ppm was made to iron that was not inoculated with Bi+RE inoculant. In **Figures12** and **13**, the orange points are without Sb or Bi, while the blue points represent samples with either Sb or Bi.

As can be seen from Figure12, some improvement in nodule density might be achieved with either Sb or Bi, however from Figure 13, the effect on nodularity is not clear. The dots with zero nodule density and nodularity represent samples with chunky graphite. In total 5 samples showed chunky graphite and 4 were inoculated with Bi+RE and one with Ca+RE.

Case Study – Automotive

The following example shows a conversion from EN- GJS-500-7 to EN-GJS-600-10 for a steering knuckle seen in **Figure14**.

Normal production of steering knuckle in EN-GJS-500-7 often experience problems with carbides in the thin section of the casting and shrinkage in the thicker boss area of the casting.

In **Table7** the final composition is presented for EN-GJS-500-7 compared with EN-GJS-600-10. The same raw materials were used for the charge make up, 20% steel scrap, 15% pig iron and 65% returns. For EN-GJS-600-10 additional Si-units were added to hit target Si-level, while for EN-GJS-500-7 alloy addition with Cu was required to achieve desired mechanical properties.

In **Figure15** the typically etched structure for EN- GJS-500-7 is compared with the etched structure for EN-GJS-600-10 and as can be seen a fully ferritic structure is achieved.

In **Table8** the mechanical properties are compared for test bars taken from the casting as specified by the customer.

Based on the results achieved it was

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concluded that EN-GJS-600-10 could be a replacement for EN-GJS-500-7. Due to improved properties the customer has indicated that a 5% reduction in weight would be possible. The fully ferritic matrix and overall lower hardness should also make it possible to achieve longer tool life in machining.

Case Study – Wind Energy

In 2014 one of the largest wind generator casting producers were approached with regard to producing ductile iron castings in EN-GJS-600-10. The reasons for producing this grade were to allow for castings to have thinner wall sections and reduced final casting weight.

Initial trials were made on step block moulds with a maximum thickness of 400mm; many trials were conducted using different Si levels and metal treatment packages. **Figure16** compares the microstructures of the 2 materials. **Table9** summarises the trepanned samples mechanical properties.

A 2.5MW bed plate casting which had previously been produced in EN-GJS-400-18U-LT with an as cast weight of 20.5mt was compared to a bed plate cast in EN-GJS-600-10 but with a 30% lower weight.

The main differences between the specifications of the two materials were that the new grade of SSF did not possess the same low temperature impact properties. This difference in the specification was accepted by the end customer.

The EN-GJS-600-10 went into production in the second half of 2015 and the foundry continues to supply approximately 60,000 MT of castings seen in **Figure17** in this material annually.

Summary

Solution Strengthened Ferritic Ductile Iron (SSF) was originally developed as a substitute for standard ferritic-pearlitic ductile iron used in automotive applications. The interest in SSF iron was sparked by its higher uniform hardness,

Table6: Effect of cover material on structure and properties of SSF

Cover Type	Steel Punchings (44 values)	Specialty FeSi (26 values)
Nodule Density, N/mm^2	254	296
Nodularity, %	64	76
Yield Strength, MPa	478	496
Tensile Strength, MPa	577	590
Elongation, %	12	14

Figure11: Variation in nodule density for different inoculant types tested

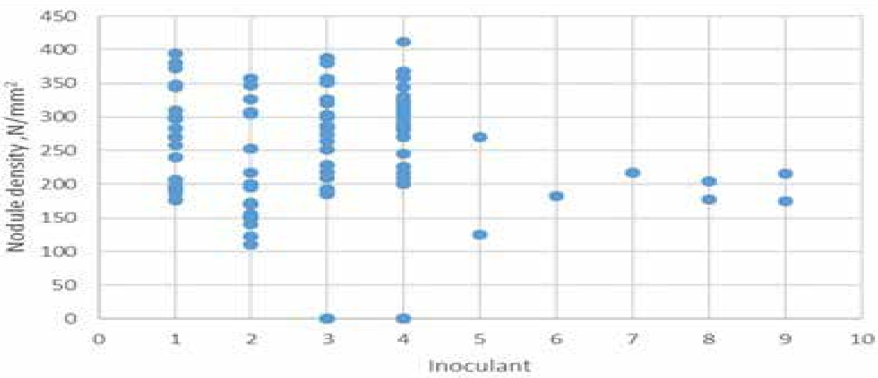


Figure12: Comparison of nodule density with Sb or Bi and without Sb or Bi

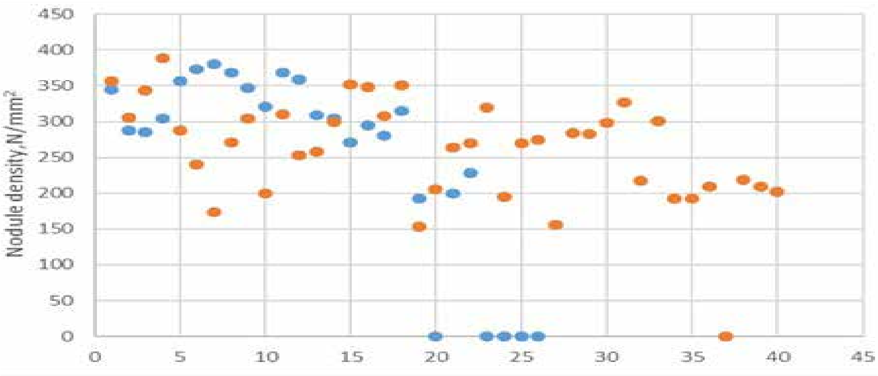


Figure13: Comparison of nodularity with Sb or Bi and without Sb or Bi

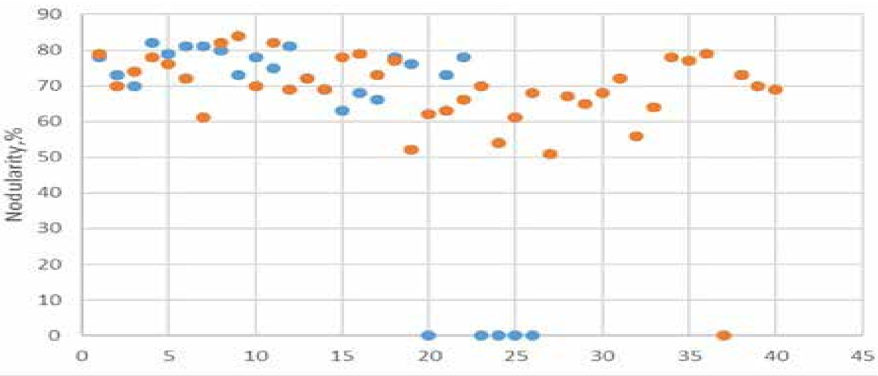
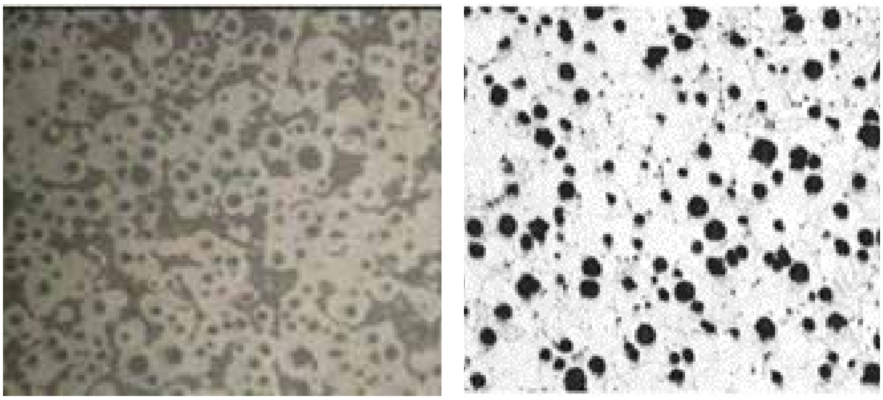


Figure14: Steering knuckle casting

Table7: Comparison of chemical composition

	EN-GJS-500-7	EN-GJS-600-10
%C	3.65	2.96
%Si	2.50	4.22
%Mn	0.22	0.22
%S	0.010	0.010
%Mg	0.042	0.053
%Cu	0.30	Trace level

Figure15: Comparison of typically structure in etched conditions



EN-GJS-500-7 **EN-GJS-600-10**

lower machining cost due to the single matrix in the iron and a potential weight reduction in automotive conversions.

SSF provides higher elongation in combination with higher strength. Compared to ferritic-pearlitic grades the single matrix of SSF will provide more uniform properties regardless of section size.

Today, however, the wind-energy market is pushing this material forward because designers are interested in the material's higher yield strength and elongation – a combination that can allow considerable weight reduction in the finished casting.

The study conducted by Elkem showed that the treatment process using a combination of different MgFeSi alloys and cover materials had a more significant impact on the structure and properties of SSF iron than the choice of the inoculant. In fact, various MgFeSi alloys and cover materials were found to increase upto 50% higher nodule density and graphite nodularity, regardless of the type of inoculant.

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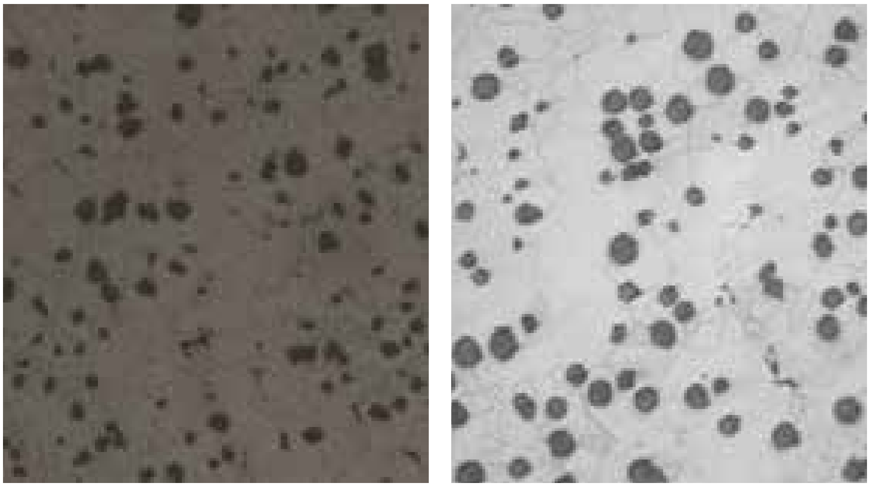
Table8: Comparison of mechanical properties

	EN-GJS-500-7	EN-GJS-600-10
Yield Strength, MPa	328	390
Tensile Strength, MPa	509	607
Elongation, %	8.9	14
Hardness, HB	210	196

Figure 16: Comparison of typically structure in etched conditions



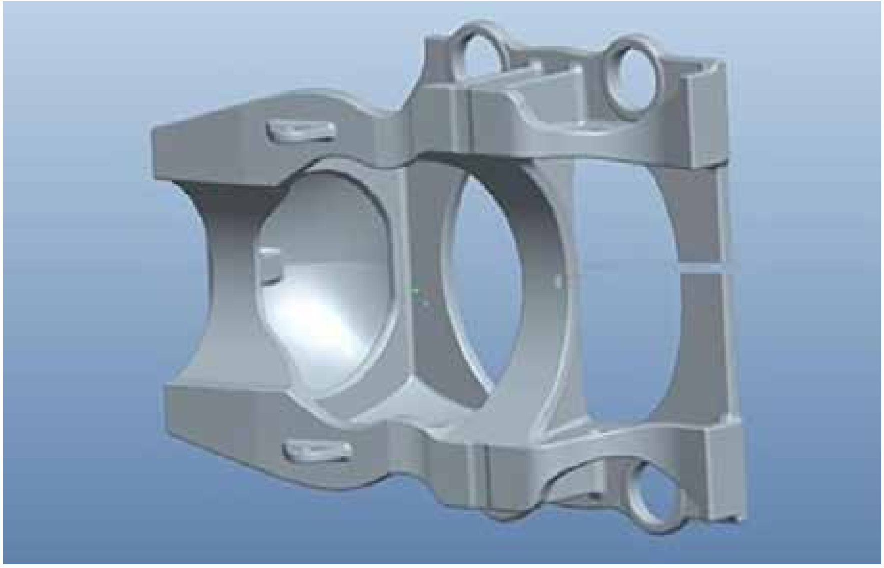
EN-GJS-400-18U-LT

EN-GJS-600-10

Table9: Comparison of mechanical properties of trepanned samples from casting

	Tensile MPa	Yield MPa	Elongation, %	Hardness, BHN	Charpy Impact at -20°C, J
EN-GJS-400-18LT	379	250	24.7	1	11 Notched test piece
EN-GJS-600-10	525	417	19.9	184	7.8 Un-notched

Figure17: Bed plate casting converted to SSF



7. W Stets, Solution Strengthened Ferritic Ductile Cast Iron According DIN EN 1563: 2012- Properties, Production and Application, Keith Millis Symposium, 2013

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This paper was originally presented at the 67th Indian Foundry Congress held during January 18-20, 2019 in Greater Noida, UP. It was first published in Indian Foundry Journal, Vol 65, Issue 4, April 2019. Reprinted with the permission of the publishers