GREY CAST IRON FOR THE AUTOMOTIVE INDUSTRY

Oddvar Knustad, Cathrine Hartung and Lena Magnusson ¯berg

Abstract:

Is grey iron still a good alternative to aluminium and compacted graphite iron in the production of automotive castings? The paper review resent results published regarding the effect of structure on mechanical and thermal properties of grey iron. Special considerations are taken to the influence of some specific alloying elements like vanadium and nitrogen. A process for producing high strength grey iron with good thermal properties and good machinablilty is presented.

Keywords: grey iron, automotive, nitrogen, vanadium

Introduction:

In order to reduce the energy consumption and the emission from the rapid growing automotive sector there has been a continuous development on making lighter and more efficient engines for both passenger cars and trucks. In Europe emission legislations have been given in Euro 1 (1992) to Euro 6 (2014). Euro 5 and 6 will increase the requirements on NO_x- and particle emission which might be easier and cheaper to achieve by the petrol than the diesel engines. This again means that the petrol engines have to be more efficient to achieve the CO_2 requirements.

For the automotive industry the consumption and emission requirements have lead to changes where they have to produce lighter and more efficient engines. Weight reduction has partly been done by changing from engine produced in iron to engine produced in aluminium or combinations of materials. In Europe the ratio of engines produced in aluminium has developed from quite low 10-15 years ago up to approximately 50% in 2007. From 2007 the ratio between aluminium and iron has been constant, but now it seems like the iron engines will grow more rapidly than aluminium engines and in 2012 it is estimated that 60% will be iron and 40% aluminium engine blocks in Europe, see fig. 1[1].

There are several reasons for this development. One is that the efficiency requirements for both diesel- and petrol- engines have increased the combustion pressure and mechanical stress on the materials that has made aluminium reach its limit. Another is the lightweight and downsizing development that has been going on in the iron foundries. See fig 2 and fig 3 for weight comparison and example of downsizing [1].

Material consideration:

Traditionally the engine blocks were made of grey iron. This is a material with good mechanical properties, good thermal properties both for engines and brake components and very good castability which in result gives a material that is very well suitable for the production of automotive castings. However due to the weight requirements grey iron has been challenged both by aluminium and compacted graphite iron, which both are more expensive and more energy consuming to produce.

Elkem AS, Foundry Products, Kristiansand, Norway

To comply with these challenges the grey iron foundries have to make grey iron grades with better mechanical properties compared to the traditional grades for engine cylinder blocks. There are several ways of increasing the strength of grey iron. The main factor controlling the strength of grey iron is the size and length of the graphite flakes. The most important factor controlling the size and the length of the flakes is the solidification rate. Higher solidification rate gives shorter flakes and higher strength while slow cooling gives longer flakes and thereby iron with poorer mechanical properties. The second factor is the carbon equivalent and especially the carbon content. Higher CE and higher content of carbon gives more carbon in the structure and longer flakes. See fig. 4[2]. as example of mechanical properties as function of solidifying rate and carbon equivalent. The third factor is elements that reduce the growth of the flakes, like e.g. nitrogen and vanadium. The last factor controlling the flake length is inoculation. A good inoculated iron typically has a higher cell count and thereby shorter flakes compared to poorly inoculated irons. However the main benefit by having good inoculated iron is that it is very efficient in reducing cementite formation in thin sections and thereby improving the machinability. So the most obvious things to do to improve the strength in grey iron are increasing the solidification rate or reducing the carbon equivalent CE. There are however disadvantages with both these methods. A lower CE will reduce the castability and increase the probability for shrinkage defects and carbide formation. Increased solidification rate means increased risk for carbide formation.

Due to this it is interesting to look for other ways of refining the graphite structure without reducing the carbon equivalent and thereby the good castability and machining properties of the grey iron.

M.C.McGrath et al [3] has studied the effects of nitrogen, aluminium and titanium in grey iron and concluded that these elements changed the graphite flake length. Nitrogen shortened the graphite flake length while flake lengths increased with additions of aluminium and titanium. They believe that both aluminium and titanium will form stabile nitrides and that the beneficial effect of nitrogen therefore is neutralized. K. Eriksson et al has developed a grey iron grade that they claim to have sufficient strength to withstand the high cylinder pressure in the new generations of engines. According to their claim the iron grade has good machinability and they are able to produce without gas porosity. The main solution is to add and control the nitrogen content in the iron to be in the range 0.0095 – 0.0160%N, see fig. 5[4]. Elements like Ti and Al that will react with nitrogen have to be controlled to a low level both to avoid that the beneficial effect of nitrogen is lost and also to avoid the formation of hard titanium nitride particles that will create machining problems.

One other element that refines the graphite structure is vanadium.

A.M.Sage and J.V.Dawson[5] concludes in several reports that vanadium addition to grey iron, alone or in combination with molybdenum has the potential to give higher strength than the grades normally used for brake components. An addition of 0.4%V to a 3.6%C grey iron can produce iron with tensile properties equal to grey iron with 3.2%C (having UTS over 250MPa) and with the resistance to thermal fatigue of unalloyed 3.6%C grey iron. They claim that the chilling tendency of high carbon grey iron containing V is very low when also alloyed with Cu and given good inoculation.

P.S Mitchell[6] has re-analysed and summarized results by A.M.Sage and J.V Dawson. The effects of V and Mo on chilling tendency and mechanical properties are given in Table 1 and 2. He concluded that moderate addition of V plus Mo in grey iron with high CE only gave a slight increase in chilling tendency. This increased chilling tendency could be controlled by inoculation prior to casting. The mechanical properties showed that the effect of V on strength was approximately double of the effect of Mo, and when added in combination the effects were broadly additive.

Microstructure and eutectic cell structure are given in fig. 6 and 7 showing that the addition of V and Mo gives a more refined graphite structure at the same CEV with shorter and more uniform graphite flakes. The eutectic cell structure was finer and a higher number of cells could be seen when alloyed with V compared to unalloyed iron. Finally the pearlite lamella spacing indicated that the V addition refine pearlite by reducing the lamella spacing as seen in fig 8.

Dirk Radebach[7] confirms the effect of vanadium given by other authors. He found that the effect on strength has a maximum point for a given vanadium content and that further increased vanadium addition reduced the strength as shown in figure 9. This is explained by increased content of large vanadiumcarbide that act as notches in the structure. He explains the increased strength by the refining of the graphite structure with more rounded graphite flakes as shown schematic in fig. 10.

Discussion:

From the studied literature it seems like nitrogen is an efficient element to increase the strength in grey Iron. There are however some challenges and limitations when using nitrogen as strengthening element. One is to ensure that the nitrogen does not generate porosity in the form of so called nitrogen fissures. The risk for nitrogen fissure increases when the section thickness increases and it is suggested that a relationship between maximum section thickness and nitrogen content has to be established. Another issue is that nitrogen will react with some common elements used in inoculant and form nitrides. It is therefore suggested that when nitrogen is used, a inoculant with low content of zirconium and aluminium is used e.g. a Sr based inoculant like Superseed® 75 inoculant. This inoculant is without Zr and also has low aluminium content.

When systems containing V and/or Mo are used for increased strength the most probable defect is carbide in the casting and thus poor machinability. In systems that are prone to give chill it has been shown that combination of preconditioning using a Zr and/or Al containing preconditioner in combination with an efficient inoculation has been very efficient in reducing the chill formation and improve the machinability. Figure 11 and table 3 show results from foundries making automotive castings showing the effect of preconditioning and different inoculants on chill and mechanical properties. The combination Preseed™ preconditioner and Zircinoc® inoculant has proven be very efficient in reducing the chill tendency in grey iron without reducing the strength of the iron.[8][9]

References:

[1] Weber R and Görtz W, Gusseisen – der Werkstoff für Zylinderkurbelgehäuse der neueste Motorgeneration, Eisenwerk Brühl GmbH, Brühl,

[2] Diószegi A, Fourlakidis V, Svensson I, Microstructure and tensile properties of grey cast iron, Research report 04:1 ISSN 1404-0018, Scool of Engineering, Jönkjöping University, Sweden, 2004

[3] McGrath M.C., Richards V, Anish T.V, Effects of Nitrogen, Titanium and Aluminum on Grey Cast Iron Microstructure, AFS Transactions 2009

[4] Eriksson K, Volvo LastvagnarAB, Engine cylinder block and cylinder head fabricated from a grey cast iron alloy, US Patent No.: US 7,419,554 B2, Sep. 2, 2008

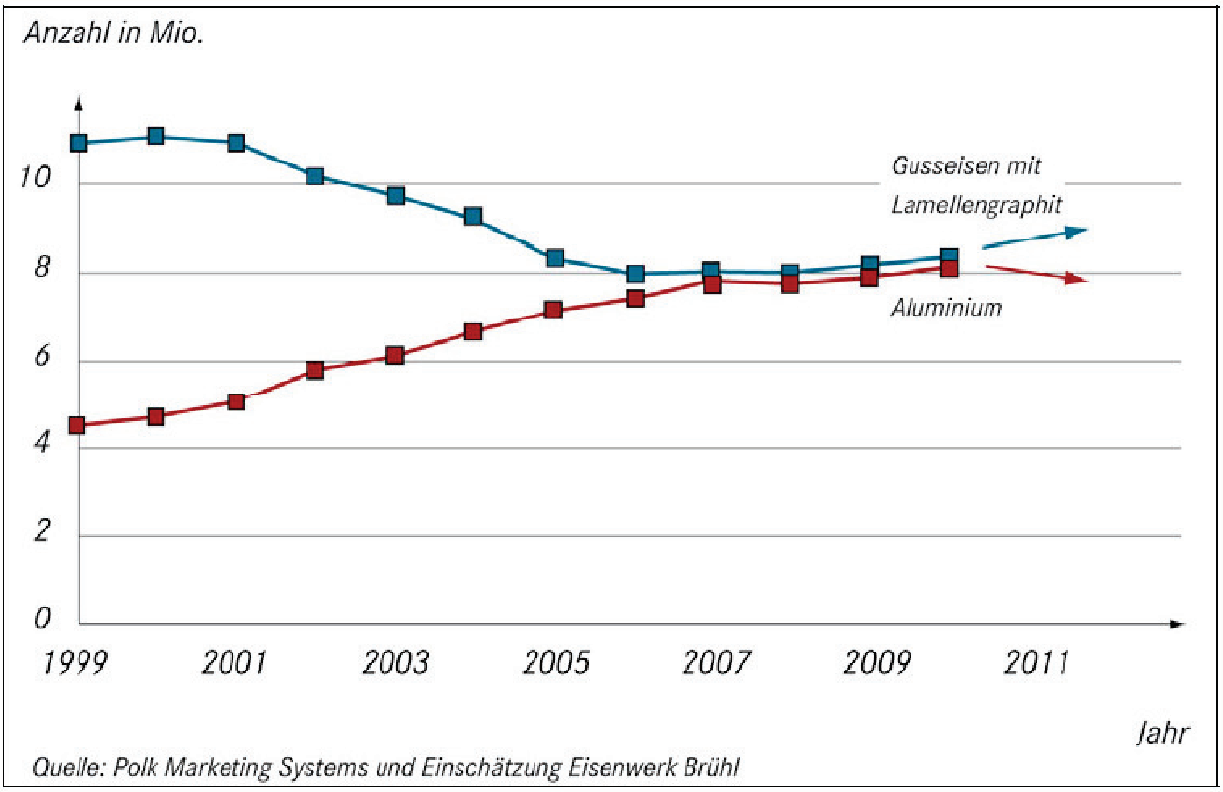
[5] Sage A. M , Dawson J. V., Development of high carbon, high strength, vanadium grey cast iron with potential application for high duty brake drums and discs, Vanitec, Vanadium International Technical Committee

[6] Mitchell P.S. The Effects of V, Mo, Ni and Cu on the Strength and Thermal Fatigue Resistance of Grey Irons Suitable for High Duty Applications (Vanitec Publication. (V0392)) Vanitec, Vanadium International Technical Committee

[7] Radebach D, Moderne Gusseisen-Werkstoffe für leichte und effiziente Downsizing-Motoren, MTZ 02I2009

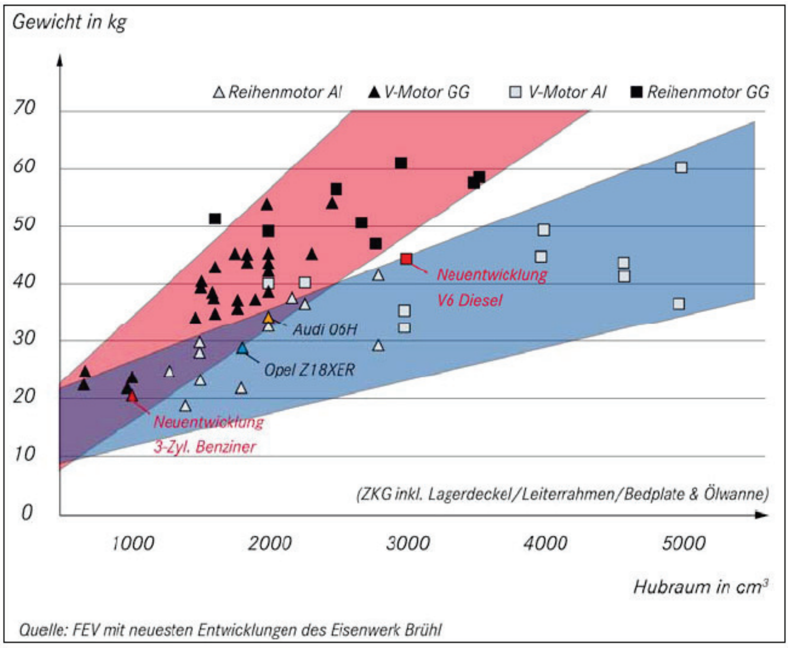
[8] Hartung C, Internal report no F173/03 Bestimmung der am besten geeigneten Gießstrahl-Impflegierung in Kombination mit der Pfannenimpfung mit Superseed®75

[9] Wilkinson D. Internal report 021005



Quelle: Polk Marketing Systems und Einschätzung Eisenwerk Brühl

Figure 1: Number of engine blocks produced by the use of grey iron and aluminium in Europe from 1999 to 2010. [1]



Quelle: FEV mit neuesten Entwicklungen des Eisenwerk Brühl

Figure 2: Weight of engineblocks produced in cast iron and in aluminium vs. engine capacity (cm^3)[1]

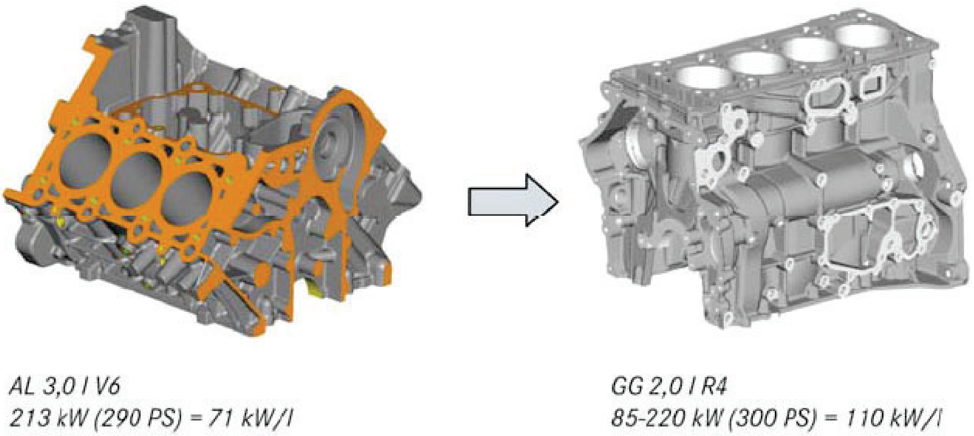


Figure 3: Downsizing, 6 cylinder Al-engine replaced with 4 cylinder cast iron engine.[1]

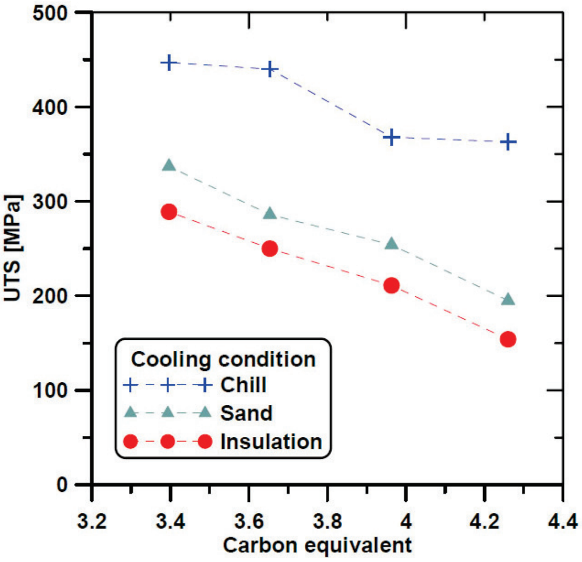


Figure 4: UTS of grey iron vs. carbon equivalent and solidifying rate[2]

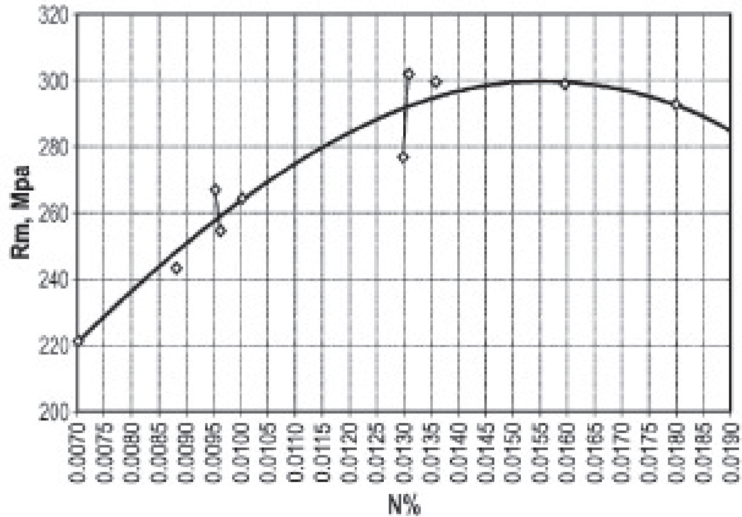
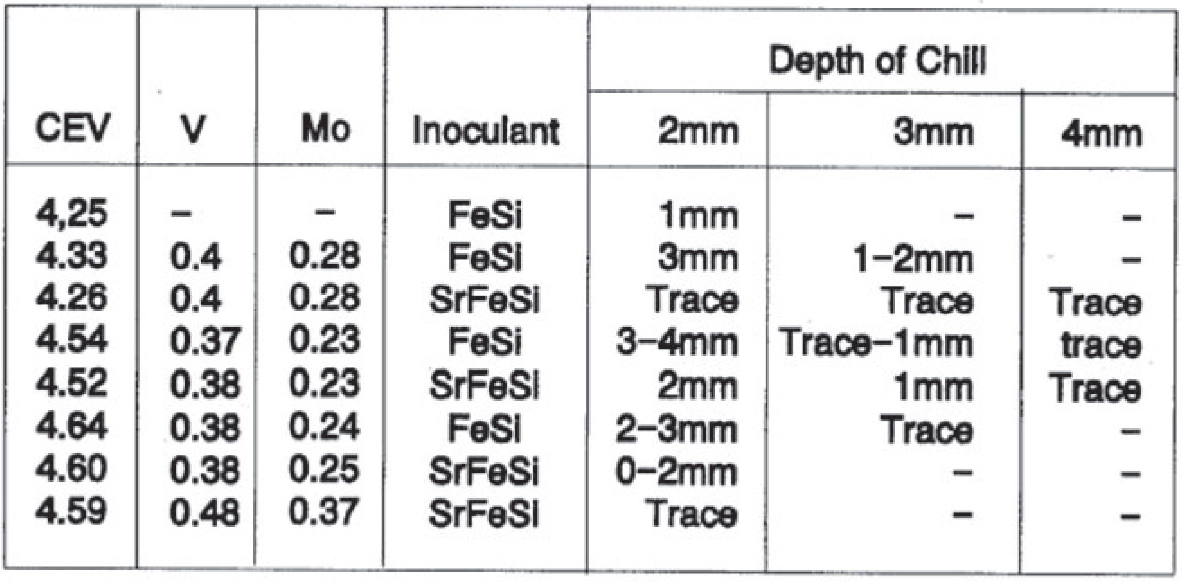


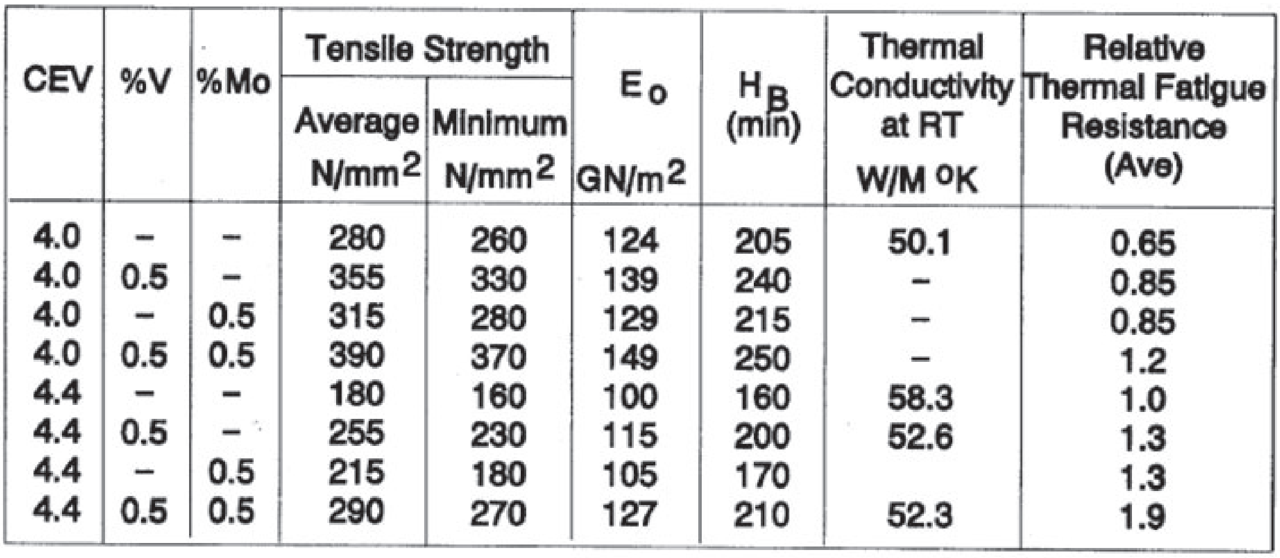
Figure 5: Tensile strength vs. nitrogen content in grey iron.[4]

Table 1: The effect of inoculant, carbon equivalent, vanadium and molybdenum on chill in grey irons. [6]

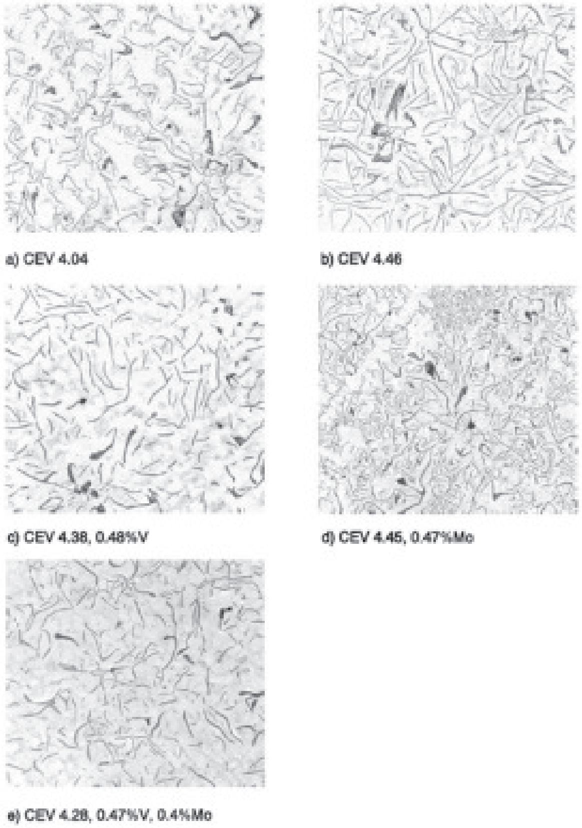


CEV	V	Mo	Inoculant	Depth of Chill		
				2mm	3mm	4mm
4,25	–	–	FeSi	1mm	–	–
4.33	0.4	0.28	FeSi	3mm	1–2mm	–
4.26	0.4	0.28	SrFeSi	Trace	Trace	Trace
4.54	0.37	0.23	FeSi	3–4mm	Trace–1mm	trace
4.52	0.38	0.23	SrFeSi	2mm	1mm	Trace
4.64	0.38	0.24	FeSi	2–3mm	Trace	–
4.60	0.38	0.25	SrFeSi	0–2mm	–	–
4.59	0.48	0.37	SrFeSi	Trace	–	–

Table 2: Summary of results of trials with vanadium and molybdenum alloying[6]



CEV	%V	%Mo	Tensile Strength		E_o GN/m^2	H_B (min)	Thermal Conductivity at RT W/M °K	Relative Thermal Fatigue Resistance (Ave)
			Average N/mm^2	Minimum N/mm^2				
4.0	–	–	280	260	124	205	50.1	0.65
4.0	0.5	–	355	330	139	240	–	0.85
4.0	–	0.5	315	280	129	215	–	0.85
4.0	0.5	0.5	390	370	149	250	–	1.2
4.4	–	–	180	160	100	160	58.3	1.0
4.4	0.5	–	255	230	115	200	52.6	1.3
4.4	–	0.5	215	180	105	170		1.3
4.4	0.5	0.5	290	270	127	210	52.3	1.9



a) CEV 4.04

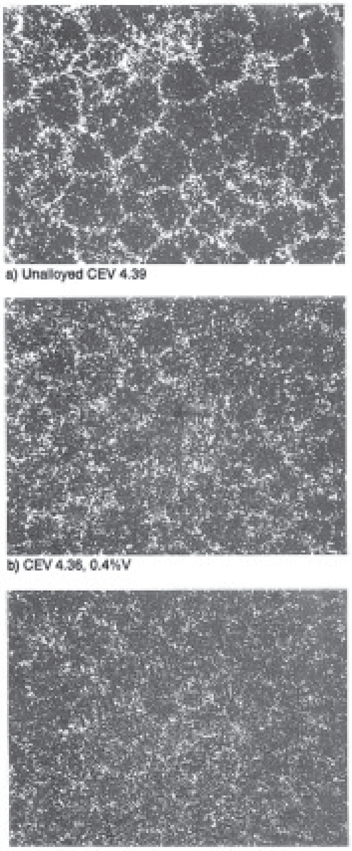
b) CEV 4.46

c) CEV 4.38, 0.48%V

d) CEV 4.45, 0.47%Mo

e) CEV 4.28, 0.47%V, 0.4%Mo

Figure 6: The effect of carbon equivalent, vanadium and molybdenum on the microstructure of grey cast irons (X100) [6]

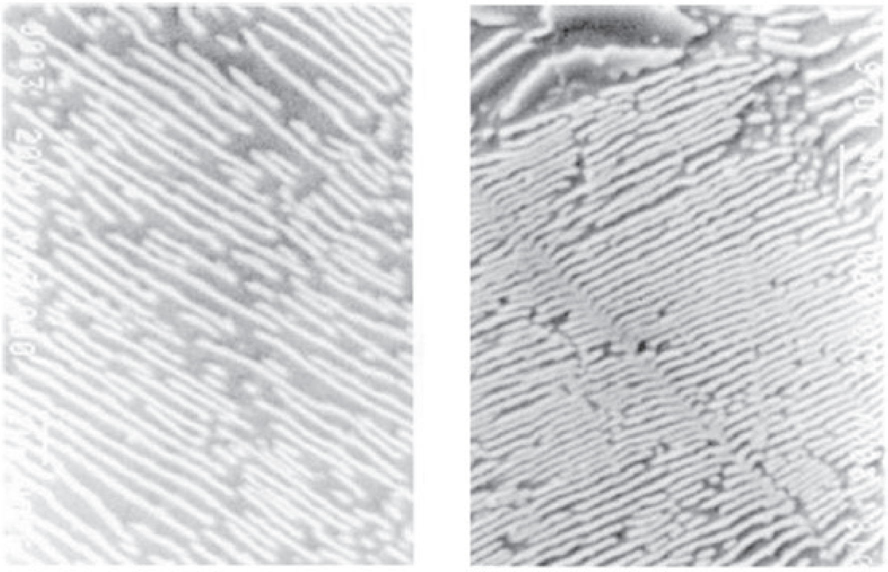


a) Unalloyed CEV 4.39

b) CEV 4.36, 0.4%V

c) CEV 4.28, 0.47%V + 0.4%Mo

Figure 7: The effect of vanadium and vanadium plus molybdenum on eutectic cell structure of grey cast irons (X20) [6]



a) Grey Iron CEV 4.39

b) CEV 4.36, 0.4%V

Figure 8: The effect of vanadium on the structure of pearlite in grey cast irons (X10.000) [6]

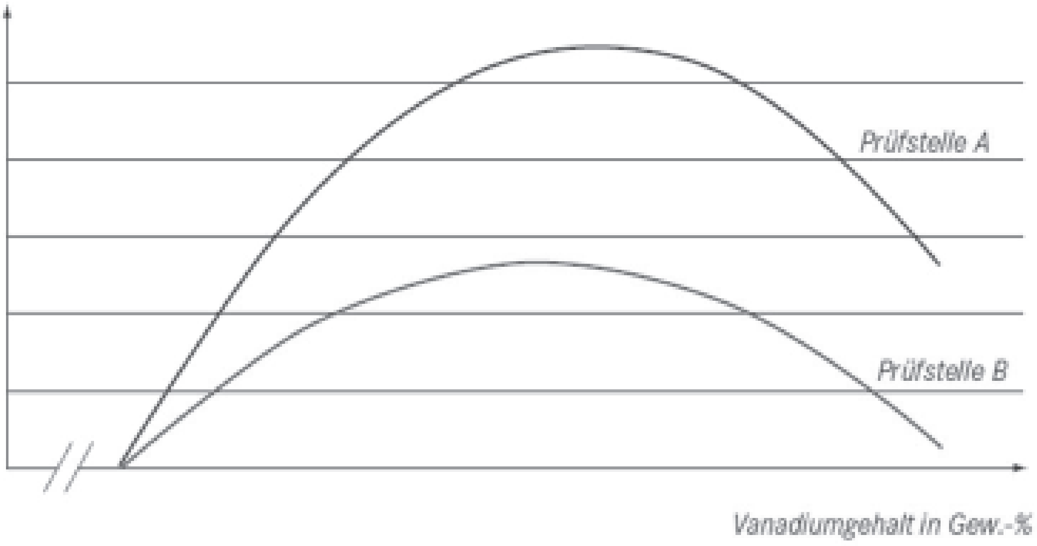


Figure 9: Tensile strength vs. vanadium content in grey cast iron [7]

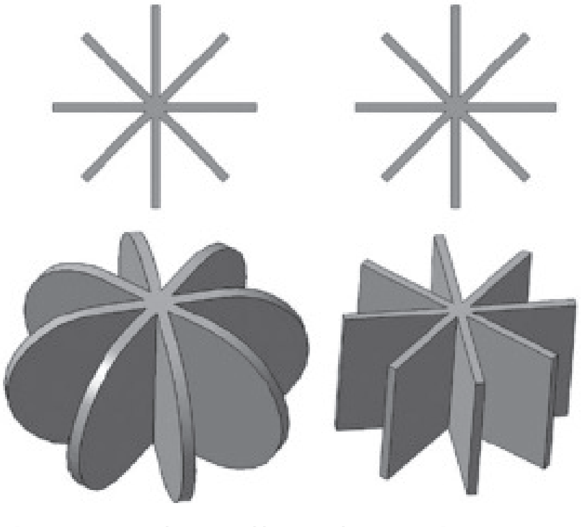


Figure 10: Schematic model of the effect of vanadium on the shape of the graphite flakes. [7]

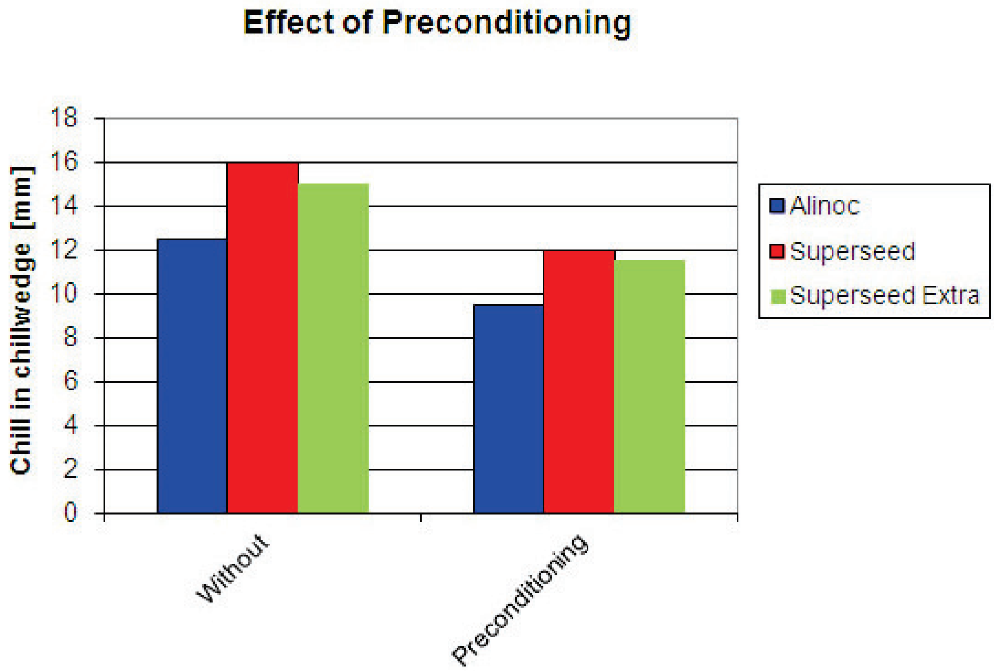


Figure 11: Effect of preconditioning using Al containing preconditioner.[8]

Table 3: Results from test with preconditioning and inoculation in UK foundry producing automotive castings.[9]

No preconditioning + 0.3% Zircinoc® inoculant	250 N/mm^2
0.1% Preseed™ preconditioner + 0.3% Zircinoc® inoculant	283 N/mm^2
Increased tensile strength by:	33 N/mm^2
No preconditioning + 0.3% Superseed® inoculant	248 N/mm^2
0.1% Preseed™ preconditioner + 0.3% Superseed® inoculant	270 N/mm^2
Increased tensile strength by:	22 N/mm^2