Future Promising for High Strength Gray Iron

Is gray iron still a good alternative to aluminum and compacted graphite iron in the production of automotive castings? Recent results from a study regarding the effect of structure on mechanical and thermal properties of gray iron address this question, taking into account the influence of specific alloying elements like vanadium and nitrogen and a process for producing high strength gray iron with good thermal properties and good machinability.

Figure 1: Shown is the number of engine blocks produced in grey iron and aluminium in Europe from 1999 to 2010.

To reduce the energy consumption and emissions from the growing automotive sector, making lighter and more efficient engines for both passenger cars and trucks is in continuous development. In Europe, emission legislations have been given in Euro 1 (1992) to Euro 6 (2014). Euro 5 and 6 will increase the requirements on NOx- and particle emission which might be easier and cheaper to achieve by the petrol than the diesel engines. This again means petrol/gasoline engines have to be more efficient to achieve the CO2 requirements.

For the automotive industry, fuel consumption and emission requirements have led to lighter and more efficient engines. Weight reduction partly has been accomplished through converting iron engines to aluminum engines or engines made with combinations of materials.
In Europe, the ratio of engines produced in aluminum grew to approximately 50% by 2007. Since 2007, the ratio between aluminum and iron engines has been constant, but now it seems iron engines will grow more rapidly than aluminium engines. In 2012, 60% of engine blocks are estimated to be in iron, compared to 40% in aluminum in Europe (Fig. 1). Several reasons exist for this development. First, 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. Second, weight and size reduction has been in development in the iron foundries (Fig. 2-3).

Material Consideration:

Traditionally, engine blocks were made of gray iron. This is a material with good mechanical properties, good thermal properties both for engines and brake components and very good castability which as a result gives a material that is very well suitable for the production of automotive castings.

However due to weight requirements, gray iron has been challenged by aluminum and compacted graphite iron, which are more expensive and energy consuming to produce. To comply with these challenges gray iron foundries must produce gray iron grades with better mechanical properties compared to the traditional grades for engine cylinder blocks.
Figure 3: The six cylinder aluminum engine (left) was replaced with the four cylinder cast iron engine (right).

Gray iron strength can be increased in a number of ways. The main factor controlling the strength of gray 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. A higher solidification rate gives shorter flakes and higher strength; slow cooling produces longer flakes and thereby iron with poorer mechanical properties.

The second factor is the carbon equivalent, especially the carbon content. Higher carbon equivalent and higher content of carbon gives more carbon in the structure and longer flakes. See Fig. 4 as an example of mechanical properties as a function of solidifying rate and carbon equivalent. Third, elements like nitrogen and vanadium can reduce the growth of the flakes.

Figure 4: Shown is UTS of gray iron vs. carbon equivalent and solidifying rate.

The last factor controlling flake length is inoculation. A well-inoculated iron typically has a higher cell count and therefore shorter flakes compared to poorly inoculated irons. However, the main benefit of well inoculated iron is it is very efficient in reducing cementite formation in thin sections, improving the machinability.
The most obvious things to do to improve gray iron strength are increasing the solidification rate or reducing the carbon equivalent. Both of these methods have disadvantages. A lower carbon equivalent will reduce the castability and increase the probability for shrinkage defects and carbide formation. Increased solidification rate means increased risk for carbide formation.

Figure 5: Shown is Tensile strength vs. nitrogen content in gray iron.

Because of this, it is necessary to look for other ways of refining the graphite structure without reducing the carbon equivalent and therefore the good castability and machining properties of the gray iron.

M.C. McGrath et al have studied the effects of nitrogen, aluminum and titanium in gray iron and concluded these elements changed the graphite flake length. Nitrogen shortened the graphite flake length while flake lengths increased with additions of aluminium and titanium.
The researchers believe both aluminum and titanium will form stable nitrides, neutralizing the beneficial effect of nitrogen. K. Eriksson et al have developed a gray iron grade they claim to be strong enough to withstand the high cylinder pressure in the new generations of engines. According to their claim, the iron grade has good machinability and can be produced 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 (Fig. 5). Elements like titanium and aluminum that will react with nitrogen have to be controlled to a low level to avoid both losing the beneficial effect of nitrogen and the formation of hard titanium nitride particles that will create machining problems.

A.M. Sage and J.V. Dawson conclude in several reports that vanadium addition to gray 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% vanadium to a 3.6% carbon gray iron can produce iron with tensile properties equal to gray iron with 3.2% carbon (having ultimate tensile strength over 250MPa) and with the resistance to thermal fatigue of unalloyed 3.6% carbon gray iron. They claim the
chilling tendency of high carbon gray iron is very low when also alloyed with copper and given good inoculation.

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

Figure 8: The effect of vanadium on the structure of pearlite in gray cast irons is shown.

Microstructure and eutectic cell structure are given in Figs. 6 and 7, showing the addition of vanadium and molybdenum 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 vanadium compared to unalloyed iron. Finally, the pearlite lamella spacing indicated the vanadium addition refined pearlite by reducing the lamella spacing (Fig. 8).

Figure 9 shows tensile strength vs. vanadium.
Dirk Radebach confirms the effect of vanadium given by other authors. He found the effect on strength has a maximum point for a given vanadium content and further increased vanadium addition reduced the strength (Fig. 9). This is explained by an increased content of large vanadium carbide that acts as notches in the structure. He explains the increased strength by the refining of the graphite structure with more rounded graphite flakes as shown in the schematic in Fig. 10.

![Schematic model showing graphite structure with rounded flakes.](image)

**Figure 10:** The schematic model shows a graphite structure with rounded flakes.

**Discussion**

From the studied literature, nitrogen appears to be an efficient element to increase the strength in gray iron. However, some challenges and limitations exist when using nitrogen as a strengthening element. One, the nitrogen must be ensured to 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 nitrogen will react with some common elements used in inoculant and form nitrides. Therefore, it is suggested that when nitrogen is used, an inoculant with low zirconium and aluminum content is used, such as a strontium-based inoculant without zirconium and with a low aluminum content.

![Effect of preconditioner with Alinoc.](image)

**Figure 11** shows the effect of preconditioner with Alinoc.
When systems containing vanadium and/or molybdenum are used for increased strength, the most probable defect is carbide in the casting and thus poor machinability. In systems prone to give chill, it has been shown using a zirconium and/or aluminium-containing preconditioner in combination with an efficient inoculation is very efficient in reducing the chill formation and improving machinability. Figure 11 and Table 3 show results from automotive metalcasting facilities using preconditioning and different inoculants on chill and mechanical properties. The combination preconditioner and zirconium inoculant has proven to be very efficient in reducing the chill tendency in gray iron without reducing its strength.