Niobium alloying in grey cast iron for vehicle brake discs

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Abstract

Niobium when alloyed to hypo- as well as hypereutectic iron has several beneficial metallurgical effects. It refines the eutectic cell size, graphite structure and also the lamellae spacing of the pearlite matrix. Nb affects the nucleation of graphite and can hence support inoculation. It also narrows down the temperature hysteresis between austenite and pearlite formation, which is important to cyclic heating. Finally, the ultra hard NbC particles formed lead to a markedly increased wear resistance of the material. The paper elucidates how these effects of Nb can be used to make brake discs with better properties and demonstrates processing benefits in the production of cast iron. Finally some examples of application in heavy trucks and recent passenger cars are given.

Introduction

Vehicle brake discs are exposed to substantial temperatures and stresses. The main reasons for the failure originate from abrasive wear and contact fatigue wear. Cast iron has been widely used to fabricate brake discs with a high carbon equivalent (CE) [1], [2] because:

(1) the specific heat of graphite is almost twice as high as that of cast iron, therefore the capacity of heat storage is greatly enhanced;
(2) the soft graphite absorbs vibration energy and provides excellent vibration damping [3]-[4];
(3) the notch sensitivity of cast iron is lower than that of steel [5].

The properties of grey cast iron heavily depend on the graphite morphology and volume fraction. Hecht [8] found that the thermal conductivity is related to the carbon equivalent in cast iron materials and flake-like graphite is favorable to improve the thermal conductivity. Currently, the carbon equivalent of grey cast iron used in brake discs usually ranges from 3.8% to 4.6%. However, although it is necessary to ensure a high thermal conductivity [6], excess graphite would cause a decrease of the mechanical properties. Under this condition, alloying with some trace elements was considered to be a probably effective remedy. Some work on niobium alloyed cast irons has been performed in recent decades including the effect of niobium on the phase transformation temperature, micro-hardness, graphite morphology and NbC particle precipitation [7]-[12]. This research work with regard to the effect of niobium in cast iron allows making the following general statements:

- Nb additions up to 0.3% improves the mechanical properties of gray iron resulting from a reduction in the cell size and correspondingly blunt graphite flake size.

- Nb decreases the tendency to produce chill carbides due to an inoculating effect and the increase in cell count.
- Nb is a mild pearlite stabilizer and refiner.
- Nb additions of more than 0.5 weight percent leads to the formation of primary MC-type carbides of high hardness improving the wear resistance of cast iron.

The optimization of brake rotor casting alloys with respect to obtaining a high damping capacity was investigated by Saturn Company (GM) [13]. In order to maintain rather coarse graphite a hypereutectic composition such as 3.8%C – 2.5%Si – 0.7%Mn – 0.25%Cr – 0.20%Mo – 0.09%Nb was found to perform best. Alloying elements such as chromium and molybdenum, which increase hardenability, guarantee the formation of a pearlitic microstructure, thus offering appreciable strength. The refinement of the eutectic cells by niobium microalloying of up to 0.09% is the key parameter to simultaneously optimize strength and damping capacity. Besides the fact that the eutectic cell exhibited practically half the size when adding 0.09% Nb also the interlamellar spacing of the pearlite became refined.

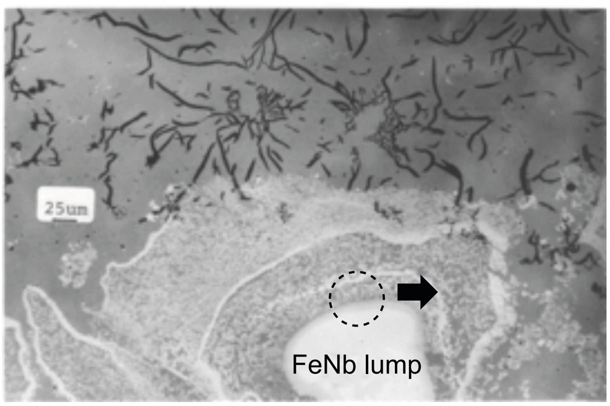
In utility vehicles, however, particularly with long-haul trucks or construction site vehicles, which are much heavier than passenger cars, the specific load on a brake is far higher as more kinetic energy needs to be dissipated. Furthermore, life expectancies are also much higher than those for passenger cars. In this case, a life in the range of several hundreds of thousands of kilometers is expected of a brake drum before replacement is required. Because of that, brakes of utility vehicles have been constructed as drum brakes until recently. Drum brakes have a much lower specific stress level in comparison to disk brakes. However, due to various advantages in comparison to drum brakes, disk brakes have been introduced in utility vehicles in the 1990's. Grey cast iron alloys used for utility vehicle brake drums could not be used for utility vehicle disk brakes due to the higher stress levels and the risk of heat cracking.

For that reason grey cast iron alloys for brake disks had to be optimized with regard to higher service life and reduced heat crack formation. A high-carbon hypereutectic iron base material with good thermal conductivity has been developed as base alloy by Mercedes-Benz [14]. The soft basic structure has insufficient stability and hardness due to the high carbon and silicon contents. Adding niobium in the range of 0.3 to 0.4% to the alloy successfully regained strength. Again, niobium's effect was to refine the eutectic cell structure, thus increasing the strength. Furthermore a complete and mainly finely lamellar, pearlitic basic structure could be obtained. The latter is likewise important for the high tensile strength and hardness. According to the wall thickness of the brake disk, the silicon content had to be appropriately adjusted as to obtain a Brinell hardness of approximately 150 to 190 HB. In the fine-pearlitic basic structure, niobium carbides with an approximate hardness of 2400 HV are embedded in a uniformly distributed manner and reduce wear during the braking operation. The machinability of the cast alloy with the fine-pearlitic basic structure was acceptable after adapting tool materials and machining parameters. Benchmark testing has shown that discs made from Nb alloyed grey hypereutectic iron can achieve at least 8-times the life of brake pad linings. The Nb-alloyed hypereutectic grey iron was initially used for the brake discs of the heavy Mercedes "Actros" trucks. Over the years, the alloy penetrated into Mercedes' smaller tucks and also passenger cars.

Lacking a thorough understanding of the detailed metallurgical effects of Nb in grey cast iron, a research project was launched at the Shanghai Key Laboratory of Modern Metallurgy & Materials Processing (Shanghai University) with the support of CBMM-CITIC. The effect of niobium on the formation of NbC phase and solidification structure in high carbon equivalent grey cast iron was investigated. Simultaneously, industrial trials and serial introduction of Nb-alloyed brake disks were done in cooperation with Shanghai Huizhong Automotive Manufacturing Company for Volkswagen PQ35 models and Rover 75.

FeNb dissolution in cast iron and alloying practice

The standard Nb compound for addition to iron is ferroniobium with about 66% Nb. This composition almost corresponds to the intermetallic phase FeNb, known as the μ-phase in the Fe-Nb phase diagram (13). Ferroniobium has a rather high melting point with a solidus and a liquidus temperature of 1580°C and 1630°C, respectively. Consequently, this alloy does not melt but has to be dissolved. A dissolution mechanism applies, as is explained by the following micrographs (14). Figure 1 shows an undissolved FeNb lump present in frozen cast iron. The lump is surrounded by concentric rings. The mechanism of dissolution becomes clearer at increased magnification of the interface between the ferro-niobium and the frozen melt. On the surface of the FeNb, several phases are visible exhibiting higher carbon content than the FeNb itself. Only the surface particles of a few microns in size are released to the melt. In the vicinity of this diffusion layer a large number of graphite flakes can be seen suggesting that the released particles act as nucleation site.



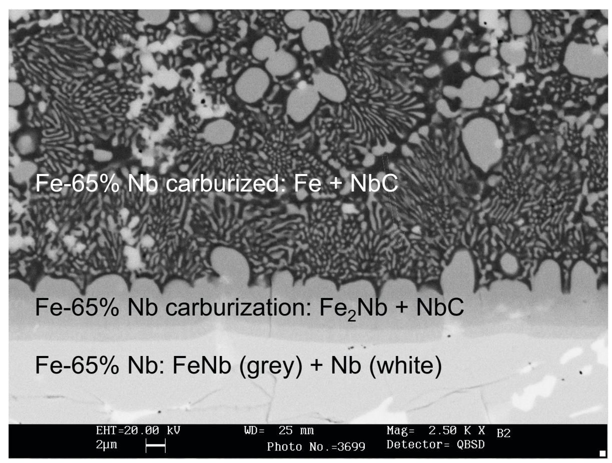


Figure 1: Dissolution layer around a FeNb (66%Nb) lump in eutectic iron.

The Fe-Nb-C diagram explains the nature of the different phases seen in this reaction. First the surface picks up carbon, thus, besides the μ-phase (FeNb) also the λ-phase (Fe_2Nb) as well as niobium carbide (Nb_2C) are observed. However the carburization is continuing and finally Nb_2C and NbC are released to the melt. As a result of the carbon surplus, only NbC will exist in the melt that will be dissolved to an extent allowed by the equilibrium, i.e. around 0.8% Nb at 1500 °C (see Figure 2). During down-cooling, however, the dissolved niobium will re-precipitate and form NbC particles again. At Nb contents above 0.1% primary carbides can already form in the liquid phase. The size of these particles is not related to that of the parent NbC particles that had been released to the melt during the dissolution of the ferroalloy**.** Figure 3 shows the calculated time required for complete dissolution of a given FeNb lump diameter. Some turbulence in the molten bath, which can be obtained by stirring or injection, accelerates the dissolution kinetics. Considering a typical melting temperature of 1400 °C in a foundry, Figure 3 predicts a period of approximately 15 minutes for the dissolution of a FeNb lump of 12 mm (1/2 inch) diameter.

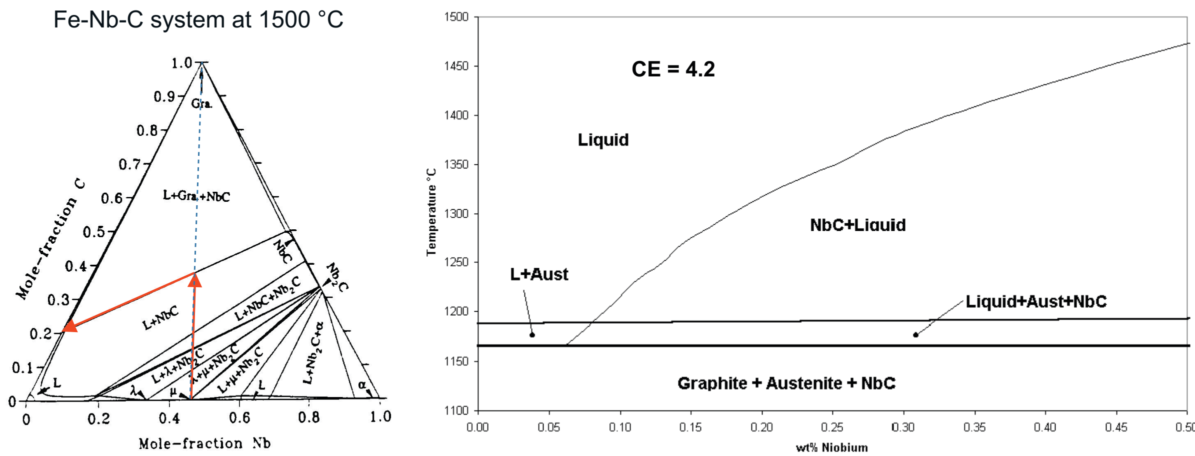


Figure 2: Phase diagrams indicating the mechanism of FeNb dissolution (left) and re-precipitation of solute Nb (right).

Consequently, several methods can be practiced to alloy FeNb in an efficient way:

- Lumpy FeNb is charged together with solid scrap directly to the furnace, thus allowing a long holding period at high temperature.
- In case FeNb is added during tapping only little time until casting remains. Rather fine-grained FeNb has to be added, being dissolved within a few minutes. Accordingly, such foundries would use FeNb of size 1-3 mm.
- The most effective way, however, is the injection of powdered material [14] as cored wire, since both, the fine particle size and bath turbulence favor a reduction of dissolution time.
- Superheating the melt in a holding furnace is an alternative means, to overcome poor recovery (Figure 4).

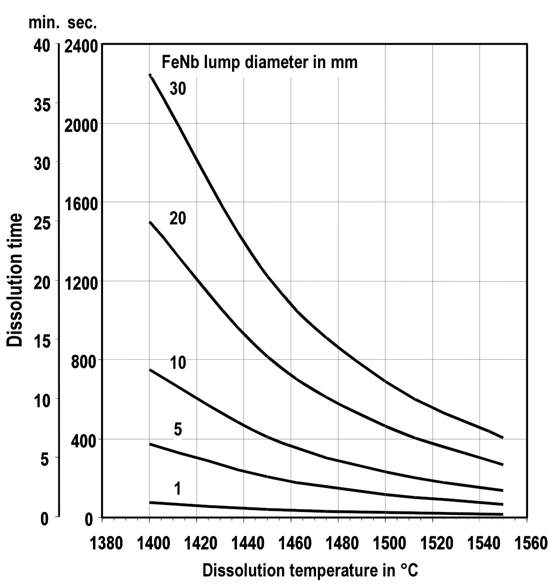


Figure 3: Dissolution time of FeNb in eutectic iron (4.23 %C) as a function of bath temperature and FeNb lump size.

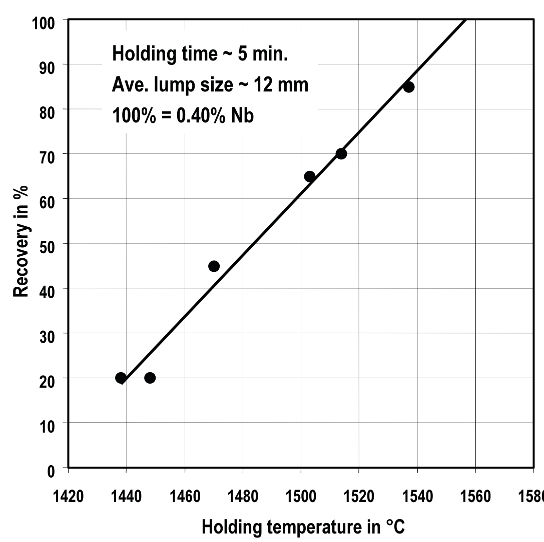


Figure 4: Niobium recovery in eutectic iron as a function of holding temperature for a given holding time and FeNb lump size.

Microstructural effects of Nb-alloying in grey cast iron

In order to clarify the effect of Nb-alloying in grey cast iron, laboratory heats of various Nb contents have been produced. The initially charged materials were clean low-silicon pig iron and steel scrap. Fe-65%Nb alloy was added to the furnace charge and treated to full dissolution. Chemical and spectral analyses were performed to confirm the designed composition. The composition of materials prepared was (mass%): 3.82%C, 2.05%Si, 0.73%Mn, 0.18%Cr, 0.08%P. The niobium content was ste to 0.042, 0.29, 0.85 and 1.48 (mass%), respectively. The alloy materials were melted at 1500°C in an 20 kg-capacity medium-frequency induction furnace and then cast into green sand moulds at 1,420°C. Optical microscopy and a scanning electron microscopy with energy dispersive spectrometry were used to observe the microstructures. The abrasive wear resistance was tested by measuring the mass loss percentage after dry grinding for 1 hour under 5 kg load. Brinell hardness tests were carried out to evaluate the effect of niobium on alloy strength.

Formation of NbC phases

For the 0.042%Nb sample, primary NbC precipitates in the final solidified structure cannot be observed in agreement with Figure 2. When the niobium content is increased however to 0.29%, a few blocky NbC phases were seen (Figure 5(a)). NbC particles with a petal shape like in Figure 5(b) are likely being formed during solidification. For higher niobium contents (0.85% and 1.48%), the temperature gap between the nucleation temperature of NbC and the eutectic temperature is large enough to allow small NbC precipitates merging and growing into blocky, triangular, X or Y shaped particles as shown in Figure 5(c-d). More work is required to clarify the nucleation and growth of the NbC phase.

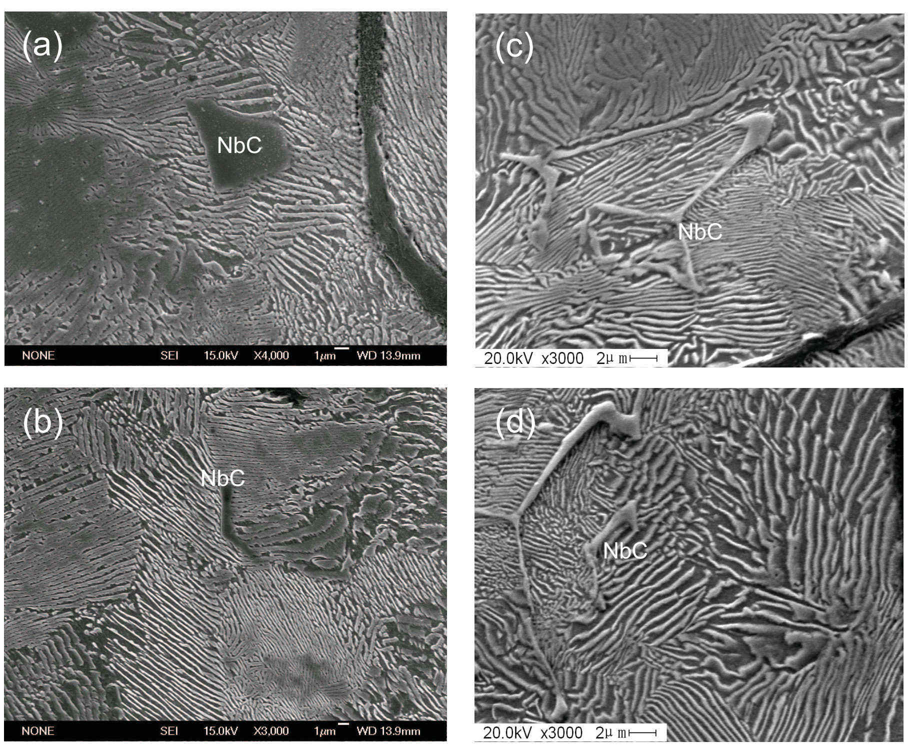


Figure 5: Morphology of NbC precipitates in cast iron.

Refinement of graphite and eutectic cell structure

Changing the carbon content or carbon equivalent is the most common method used to modify the graphite morphology [15]. The difference in carbon content and carbon equivalent of the four samples investigated in the present study is quite small. Hence its effect on graphite morphology can be ignored. Figure 6 shows the change of graphite morphology in grey cast iron for the different niobium additions. In all four samples the graphite was of type A. However, the shape and size changed greatly. Plate-like graphite and some bulk graphite distributed in the matrix were found with a niobium content of 0.042%. Increasing niobium to 0.29%, the graphite refined significantly. The finest graphite size was obtained when the niobium addition reached 0.85%. Upon further increasing the niobium content to 1.48%, the refinement effect saturated and somewhat larger graphite size was observed again. The effect of niobium content on the eutectic cell size is also obvious (Figure 7). The average diameter of eutectic cells were about 954 μm and 497 μm for the 0.042%Nb and 0.29%Nb samples, respectively. Upon increasing the niobium content to 0.85%, the diameter decreased to 298 μm. However, for a niobium content of 1.48%, the eutectic cell became larger again showing an average diameter of about 403 μm. The pattern of change in the eutectic cell is similar to that in the graphite to some extent. Data from literature obtained for the eutectic cell size in hypoeutectic grey iron as a function of various niobium additions show the same trend (Figure 8). All data suggest that the effect of niobium additions on the cell size is quite strong in the range up to around 0.2% and then levels off to a weaker effect.

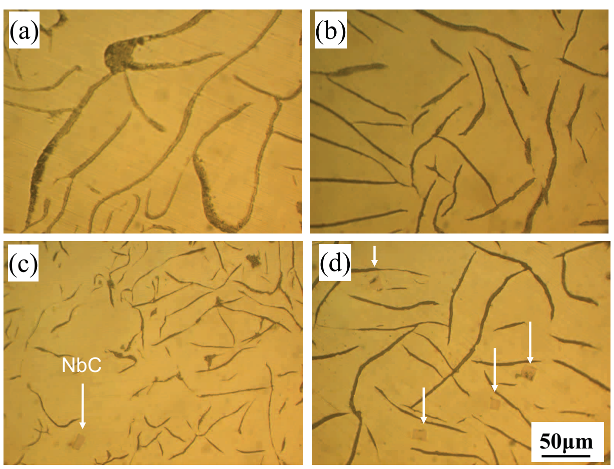


Figure 6: Graphite morphology in grey cast iron.
(a) 0.042%Nb, (b) 0.29%Nb, (c) 0.85%Nb, (d) 1.48%Nb

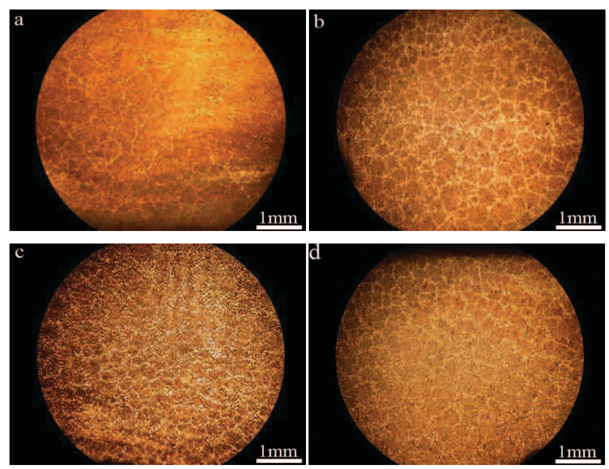


Figure 7: Eutectic cells in grey cast iron.
(a) 0.042%Nb, (b) 0.29%Nb, (c) 0.85%Nb, (d) 1.48%Nb

The refinement mechanism of niobium on graphite can be explained from the following two aspects. Firstly, small NbC precipitates merge and grow into larger particles as mentioned above. It is however inevitable that some residual small NbC precipitates do remain during cooling to the eutectic temperature, which then act as heterogeneous nucleation sites for graphite in the eutectic reaction. As a result, the increased nucleation rate results in refined graphite morphology. Secondly, niobium obstructs carbon from moving during solidification, which also restricts the growth of graphite thus keeping it small and short. When the niobium content reaches 1.48%, more primary NbC particles are being formed above the eutectic temperature.

However, it also leads to a rapid merging and growth of NbC particles because of a larger temperature gap between the formation temperature of NbC and the eutectic temperature so that most NbC particles coarsen to several micrometers of size. Only few residual small precipitates being suitable to play the role of nucleation sites in the subsequent eutectic reaction remain. This explains the observation that the graphite became slightly coarser again. The eutectic cell contains graphite and austenite. Graphite acts as the leading phase during solidification and austenite forms continuously following the graphite. Therefore, it is evident that the eutectic cell size changes similarly as the graphite.

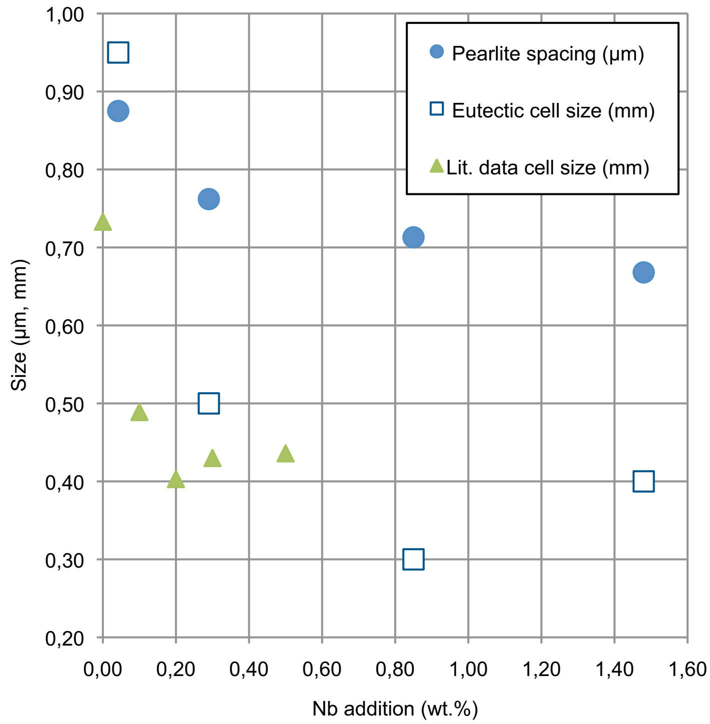


Figure 8: Effect of Nb alloy content on microstructural refinement of eutectic cells and pearlite spacing in hypereutectic grey cast iron (present study). Literature data refer to eutectic cell size of hypoeutectic grey iron [7].

Refinement of pearlite lamellar spacing

Besides the refinement of graphite and eutectic cells, the pearlite lamellar spacing is also reduced with the addition of niobium. For a niobium content of 0.042%, the pearlite spacing is about 875 nm. The pearlite spacing is reduced to about 678 nm when the niobium content reaches 1.48 %. The variation of lamellar spacing with the niobium content is shown in Figure 8.

The lamellar spacing of pearlite is mainly controlled by the austenite-to-pearlite transformation (eutectoid) temperature. A lower transformation temperature, i.e. under-cooling compared to the equilibrium temperature, promotes a higher nucleation rate and hence a finer structure is formed. The present study showed that niobium addition to cast iron decreases the transformation temperature and thus enhances the under-cooling significantly. For instance, the eutectoid transformation for 0.097%Nb cast iron is delayed by around 20°C as compared to a 0.019%Nb cast iron. Figure 9 shows the transformation start and stop temperatures of the different phases obtained from dilatometer curves for various cooling rates. An increased niobium addition reduces the ferrite as well as the pearlite start temperature whereas it increases the pearlite finish temperature. Furthermore, the diffusivity of carbon atoms is reduced not only because of the lower eutectoid transformation temperature but also due to the interaction of solute niobium with carbon [16],[17]. Both effects contribute to the reduction of pearlite lamellar spacing in cast iron with the addition of niobium.

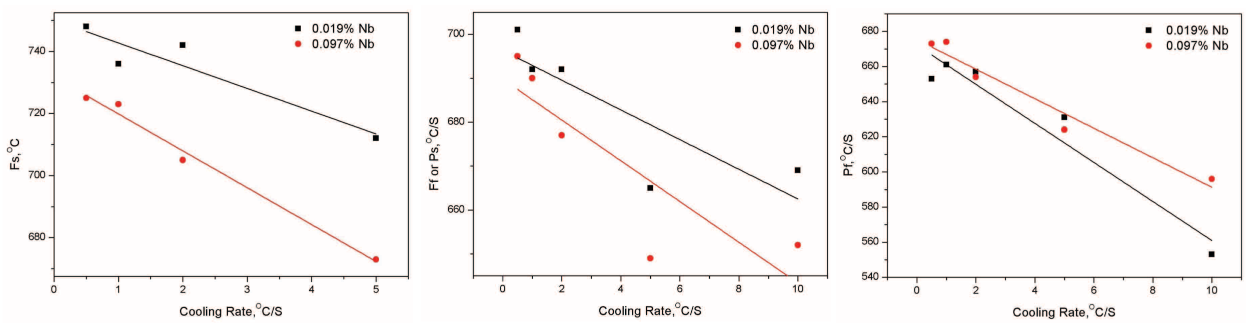


Figure 9: Transformation temperatures (F_s = ferrite start, F_f = ferrite finish, P_s = pearlite start, P_f = pearlite finish) as a function of cooling rate for two different Nb contents.

Effect of niobium on mechanical properties of brake disc alloys

Figure 10 shows the effect of niobium on hardness and wear resistance. Wear rate is defined as the mass loss percentage, i.e., the smaller wear rate indicates the better wear resistance. It is noted that as the niobium content increases, both the hardness and wear resistance improve. An increase in hardness usually promotes wear resistance whereas it has an adverse effect on the toughness of the material making it less resilient to impact loading. In the present alloys it is obvious that the refined structure (eutectic cells and pearlite spacing) is at the origin of the superior hardness. This structural refinement, however, is beneficial to toughness. In addition, the dispersion of primary niobium carbide particles in higher niobium containing alloys may form another contribution to the increased hardness. The hard phase acts as initial friction surface and constitutes a load bearing phase. For this purpose the hard phase needs to have a certain minimum size and strong embedding in the matrix phase. Very small particles can be quite easily removed from the surface by ploughing wear. Too large and branched hard particles can be detrimental to toughness. Blocky NbC particles as shown in Figure 5(a) appear to be most suitable. An advantage of niobium is that such particles are formed at temperatures well above the eutectic. This means niobium is not interfering with graphite inoculation at the eutectic temperature. Furthermore, the NbC particles are homogeneously distributed and are not concentrated on eutectic cell boundaries, which would be negative for toughness.

The effect of niobium alloying on the ultimate tensile strength was evaluated on another series of hypereutectic casts. A distinct two-stage correlation can be observed in Figure 11. Up to a niobium content of around 0.2% a strong and linear correlation of tensile strength and niobium content is seen. When further increasing the Nb content the strength however remains practically constant. It can thus be concluded that structural refinement, which is responsible for the strength increase, saturates beyond 0.2% niobium addition. This conclusion is congruent with the findings on structural refinement shown in Figure 8. It also suggests that further hardness increase beyond 0.2% niobium addition is mainly due to a load bearing effect of primary NbC particles.

The distinct effect of niobium content on the mechanical properties of grey cast iron sets out two principal alloying strategies for brake disc manufacturing:

(1) A niobium addition of up to 0.20% is recommended when aiming for the compensation of strength loss caused by an increased CE and for graphite morphology control.

(2) Niobium additions in the range of 0.25% to 0.5% should be applied in cases where a particularly high wear resistance of the brake disc is required.

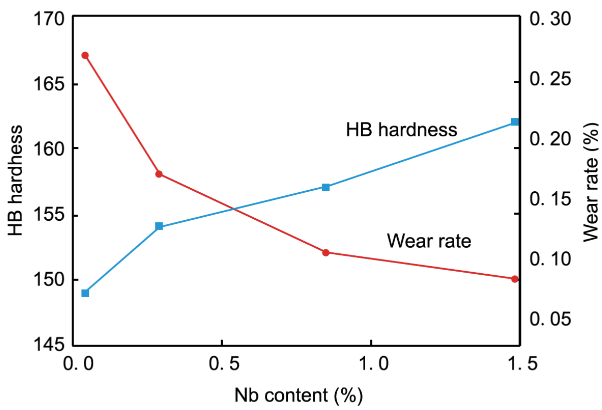


Figure 10: Hardness and wear rate (mass loss percentage) of niobium alloyed hypereutectic grey iron.

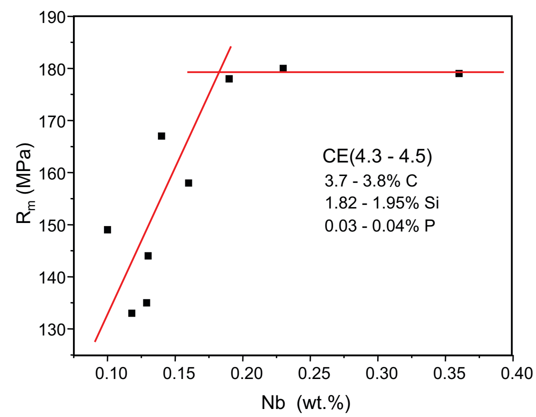


Figure 11: Ultimate tensile strength of niobium alloyed hypereutectic grey iron.

Production experience with Nb-alloying in brake discs

Mercedes-Benz was the first vehicle manufacturer using niobium alloying in grey cast iron for brake discs on a large scale. The specification DBL4007 specifies the hypereutectic grade GG-15 Cr Cu Nb HC with carbon and silicon contents in the range of 3.7% to 3.9% and 1.8% to 2.3%, respectively corresponding to a CE range of 4.3 to 4.7. The minimum tensile strength is defined as 150 MPa and the hardness requirement is 180±20 HB (5/750). The graphite morphology should be majorly of type IA, 2…5. The niobium content in the alloy is specified in the range of 0.35% to 0.45%. NbC particles should be homogeneously embedded in the pearlite matrix. With this alloy concept truck brake discs with a piece weight of up to around 42 kg are being produced. Since the in-house foundry is using one large cupola oven that generates pig iron also for all other products, direct “cold” charging of FeNb is excluded. Therefore other addition strategies have been developed. One is to add lumpy (3-12 mm) FeNb in a holding furnace operated at increased temperature to a relatively high alloying level of around 2%Nb. This iron is subsequently diluted with Nb-free iron in the casting ladle to reach the specified Nb target range. The other addition practice is to add FeNb directly to the casting ladle using FeNb fines in a cored wire. The dissolution time of the fine FeNb particles is particularly short and can be further reduced by adding exothermic agents to the cored wire. A late addition of FeNb or high temperature holding of a niobium-enriched melt prevents NbC particles from growing too coarse. It also has positive cross-effects on the graphite inoculation. Experience has shown that Nb alloying supports inoculation by FeSi and makes the process less vulnerable for fading. Furthermore the mechanical properties are more robust against variation of the CE. Due to the presence of very hard blocky NbC particles in the material, machining of the cast blanks initially proved to be very problematic. However adapting the machining parameters and selecting a better appropriate tooling could solve material the problem. By now several external foundries have qualified to supply Nb-alloyed brake discs to Mercedes-Benz.

More recently, ShangHai Huizhong Automotive Manufacturing Co., Ltd. has started mass production of niobium alloyed brake discs for passenger vehicles built by SAIC in China. This foundry opted for cold charging of FeNb lumpy material directly to the melting furnace. For two cars of the Volkswagen PQ35 platform, the models Touran and Sagitar, hypoeutectic alloys have been developed according to the VW TL011-2001 specification. The material is similar to EN-GJL-250 with a carbon range of 2.8% to 3.4% and silicon ranging between 1.8% and 2.8%. The graphite morphology is specified as IA, 4…7. Regarding the mechanical properties, hardness is specified as 220±25 HB (5/750). Wedge pressure resistance must be minimum 175 MPa (corresponding to a tensile strength of 262 MPa). During actual production, the addition of niobium was set to the range of 0.09-0.13% at a CE of 3.8-3.9%. Microstructure, hardness, and wedge pressure resistance, were all in the specified range. As expected hardness and wedge pressure resistance increased with the niobium content. Samples tested with a reduced niobium content of 0.05% showed borderline mechanical properties. Increasing the niobium content to around 0.2% resulted in a moderate gain of hardness and wedge pressure resistance. Also a refinement of graphite became evident as it appeared in a higher number of short graphite flakes. Graphite flakes disintegrate and no longer grow, but become shorter ones, and the number of graphite increased significantly. Adding around 0.10%Nb with a CE of 3.8-3.9% is an appropriate compromise of improving the cutting performance of the brake discs. The tool life is then approximately 75% of that machining Nb-free hypoeutectic iron. Again it became clear that even when the CE is slightly out of control in the production process, the material characteristics remain robust in presence of niobium alloying.

For the Rover 75 that was transferred form the UK to China, completely new brake discs were developed. The demand was a hypereutectic grade A 3…5 grey iron according to VW TL048 with high thermal conductivity and increased strength. The hardness range is specified to 150-200 HB (2.5/187.5) and the tensile strength to 150-250 MPa (R_K = 115-169 MPa). The basic requirements can be achieved by increasing the CE to 4.4 % but it is difficult to meet the requested IA, 3…5 graphite morphology in hypereutectic gray cast iron. A niobium addition of around 0.09% succeeded in achieving the required graphite morphology and the actual mechanical properties lie approximately in the middle of the specified range. Further increasing the niobium content towards 0.15% results in shorter coarse graphite as well as a moderate increase in hardness and wedge pressure resistance. When increasing the CE to 4.5% neither niobium addition can prevent the mechanical properties from becoming critically low. For the targeted alloy with 4.4% CE and 0.09% niobium addition, the machining performance is normal. Hot-cracking tests performed according to Volkswagen standard PV29954 applying a brake inertia of 38 kgm^2 showed no cracks after 500 braking cycles.

Conclusions

Only a few manufacturers have used for many years but niobium alloying in grey cast iron for vehicle brake disc applications until today. This is due to the relatively limited research fundament of what effects niobium is causing in cast iron.

The effect of niobium alloying in high-carbon grey cast iron materials was hence investigated in detail. Experimental results demonstrated that with increasing niobium addition (up to a level of around 0.2%Nb), the morphology of graphite and eutectic cell is significantly refined. Also the pearlite lamellar spacing is clearly reduced, which is mainly caused by the decrease in eutectic temperature. Furthermore, higher additions of niobium lead to the formation of a niobium-carbide hard phase, which effectively enhanced hardness and wear resistance. The specific effects are related to the size of the niobium precipitates and to the temperature of precipitation. The presence of solute niobium is reducing the eutectoid transformation temperature.

The fundamental understanding of these effects allows defining and optimizing the use of niobium alloying under industrial conditions in the foundry. Practical experience in industrial foundries revealed clearly that niobium alloying makes the production process more robust and allows achieving the specified properties more reliably. Concerning machining of the disc blanks shorter tool life has been experienced. However, by adapting tooling material and process parameters to niobium-alloyed cast iron such problems can be solved.

Acknowledgement

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