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.

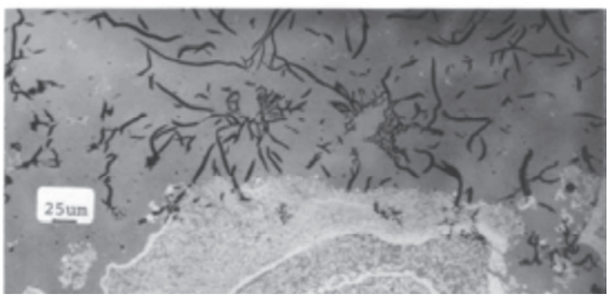

Figure 1: Dissolution layer around a FeNb (66%Nb) lump in eutectic iron.

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.