DEVELOPMENT OF FeNbC FOR WEAR RESISTANT APPLICATIONS

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Abstract

Niobium carbide (NbC) exhibits outstanding properties such as high hardness and chemical stability that are very favorable for application in high performance wear resistant materials. FeNbC is a metal matrix composite that contains fine NbC particles homogeneously distributed in an iron matrix. This innovative material was developed as an alternative alloying source of NbC and it can be applied as an additive for castings or as a hard-facing material for manufacturing wear resistant parts such as liners, chutes, pump impellers, rolling mill rolls and ground engaging tools. This work presents the properties of FeNbC and the results of dissolution trials carried out in order to determine the best addition practices for FeNbC in cast irons and steels. The most efficient methods of addition were to melt the FeNbC with the metal charge and to add it on the bath surface. It was verified that the dissolution of the iron matrix in the liquid metal allows the transfer and dispersion of NbC particles into the melt. Since the density of NbC is similar to that of melted iron and steel, the hard NbC particles distribute uniformly. Therefore, the dissolution of FeNbC enables the development of different wear resistant cast irons or steels with high contents of hard primary NbC suitable for diverse applications in the mining and processing industries.

Introduction

Refractory carbides and nitrides are useful materials with numerous industrial applications. Although most of their applications are recent, they have been known for over one hundred years. Major industrial applications of refractory carbides and nitrides involve the production of hard metals or cemented carbides, which are sintered composite materials consisting of at least one hard and wear resistant phase, in the majority of cases this being tungsten carbide (WC), and a ductile and softer metallic phase, mainly cobalt and nickel. Hard metals constitute the backbone of the tool manufacturing industry, having diverse applications such as machining of metallic and non-metallic materials, forming (wire drawing, can tooling, forging, stamping, mill rolls, punches, dies and anvils) and mining (oil well drill bits and rock drill bits). They are the material of choice in all applications where the combination of wear resistance, toughness and strength is required, at both room and high temperatures [1,2].

As shown in Table I, when compared to WC, niobium carbide (NbC) possesses similar hardness but only half of its density. Moreover, it has a higher melting point and a higher oxidation resistance. These outstanding properties make it an attractive and innovative option for most of the traditional industrial applications. NbC also has a lower solubility in iron than WC and has a similar density to materials like cast iron and steel, opening the possibility of using NbC as a raw material for hard metals [3] and for the development of new wear resistant materials for castings and hard-facing coatings with high levels of hard primary NbC homogeneously distributed in their microstructures.

Table I. Properties of Niobium Carbide (NbC) and Tungsten Carbide (WC) [1,4]

Carbide	**Density (g/cm^3)**	**Vickers Hardness (GPa)**	**Melting Point (ºC)**	**Oxidation Resistance in Air (ºC)**
WC	15.8	22	2870	500-600
NbC	7.85	19.65	3600	800

Traditionally niobium has been consumed as a microalloying element in high strength low alloy steels (HSLA). In such alloys, niobium is added as ferroniobium (FeNb) and it forms very fine NbC particles, controlling the grain size and thus improving the mechanical properties of the steel. More recently, niobium has also been applied as a very effective alloying element in cast iron, since it forms primary carbides with a homogeneous distribution. Niobium additions higher than 0.5 wt.% can lead to the precipitation of high hardness primary MC-type carbides, resulting in an improvement in the wear resistance of white cast iron, which is the main material employed when high wear performance is required in mining and earth moving equipment. Thus, NbC constitutes a promising alternative for improving erosion resistance because it forms hard and discontinuous MC carbides in cast irons. This can also be seen in indefinite chilled cast irons, materials that have been largely used in rolls for hot rolling, where the carbides improve abrasion resistance while the graphite decreases friction between the rolls and the rolled material. Additions of 1.5 wt.% niobium to indefinite chilled cast iron result in primary NbC particles that enhance hardness and wear resistance without changing the graphite morphology. As a result, improvements higher than 30% in the roll life have been reported [5].

Niobium contents of more than 5 wt.% have also been added in hard-facing materials, along with the stoichiometric amount of carbon in order to form primary NbC. The extremely hard niobium particles, finely dispersed in between the chromium carbides, have reduced spacing, ensuring the best protection from abrasive and erosive media of finer size [6].

In all these applications, niobium has been added regularly as FeNb through suitable alloying techniques, as it has to dissolve and react with carbon at its interface in order to form the hard NbC particles [5]. As an alternative to FeNb addition, CBMM has developed FeNbC, ie. niobium carbide iron matrix (NbC-Fe), a metal matrix composite (MMC) to be used mainly in applications where very high final contents of NbC are sought. This innovative material was developed as another source of NbC which can be applied as an additive for castings and hard-facing products for parts such as liners, chutes, pump impellers and ground engaging tools (GETs) for the mining and processing industry. This work presents the characteristics and properties of the FeNbC presently produced by CBMM, as well as the results of dissolution trials carried out in order to determine the best addition practices of FeNbC in cast iron and steels.

Characterization of FeNbC

FeNbC is a natural MMC that contains fine NbC particles homogeneously distributed in an iron based matrix, as shown in Figure 1.

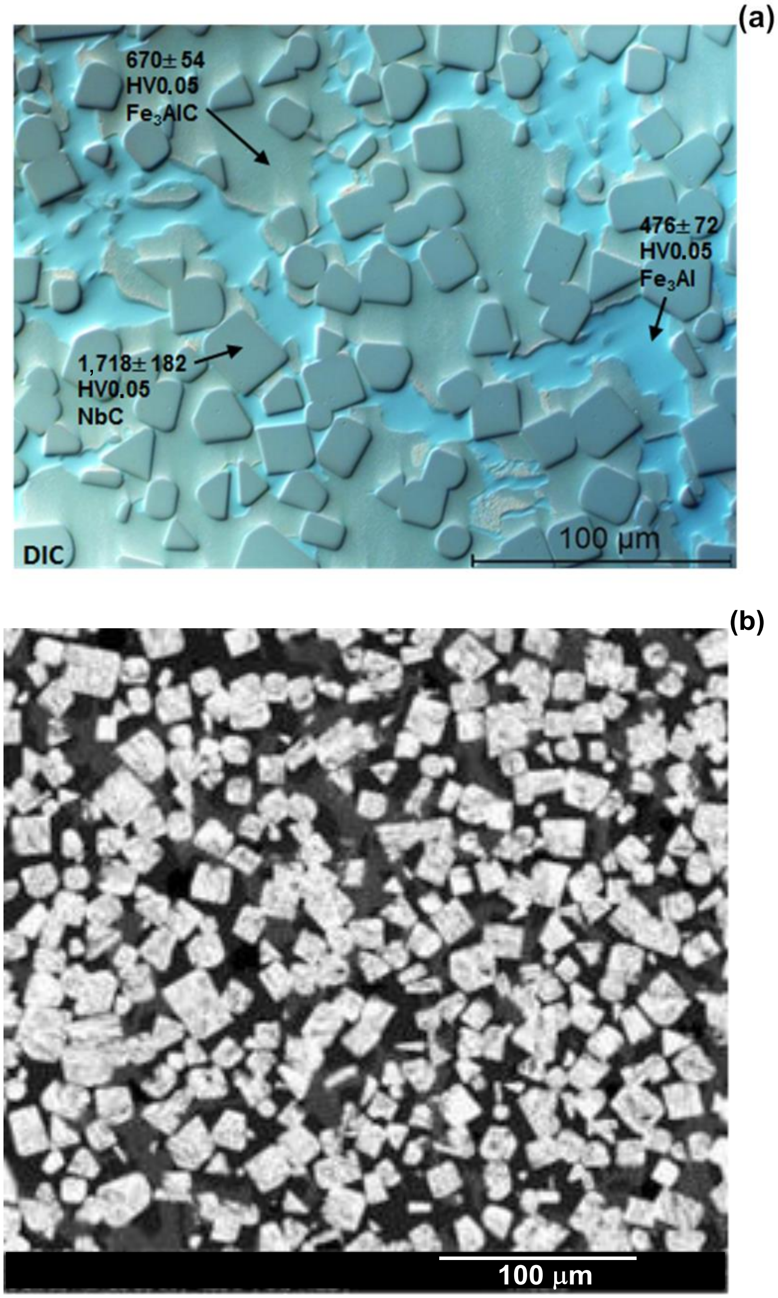


Figure 1. Typical microstructure of FeNbC shown by optical microscopy with differential interference contrast (a) and SEM/EDS (b) [7].

FeNbC is produced by an alumino-carbothermic reduction process and can be produced in a wide range of NbC contents (typically between 40 and 80% of NbC) and grain sizes between 0 and 50 mm, Figure 2.

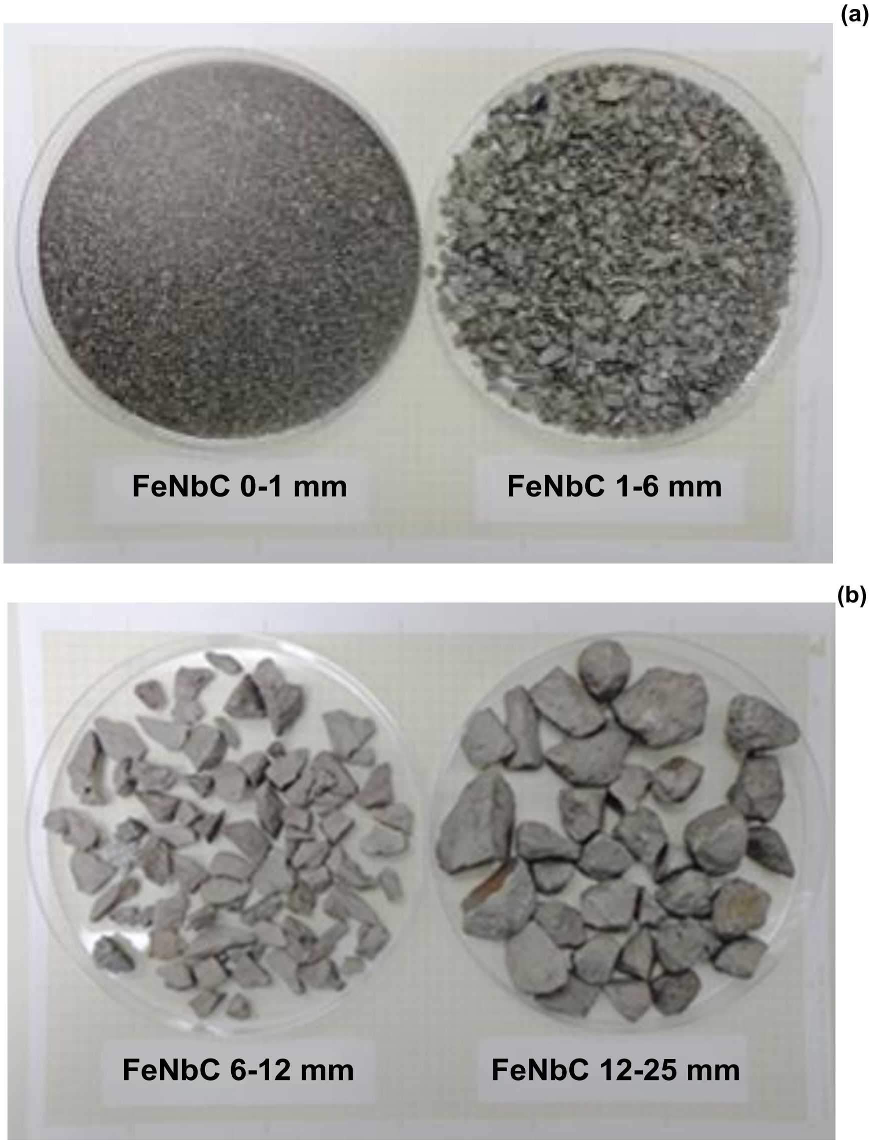


Figure 2. Appearance of different granules of FeNbC: <1 mm and 1-6 mm (a) and 6-12 mm and 12-25 mm (b).

The main phases found are NbC, Fe_3Al and Fe_3AlC, Figure 3. The microhardness of the intermetallic Fe_3Al ranges from 360 to 470 HV 0.05 and of Fe_3AlC from 630 to 670 HV 0.05 [8]. The high hardness of both NbC particles and the matrix indicate that FeNbC itself constitutes an interesting material for wear resistant applications such as hard-facing coatings for Ground Engaging Tools (GETs) [9].

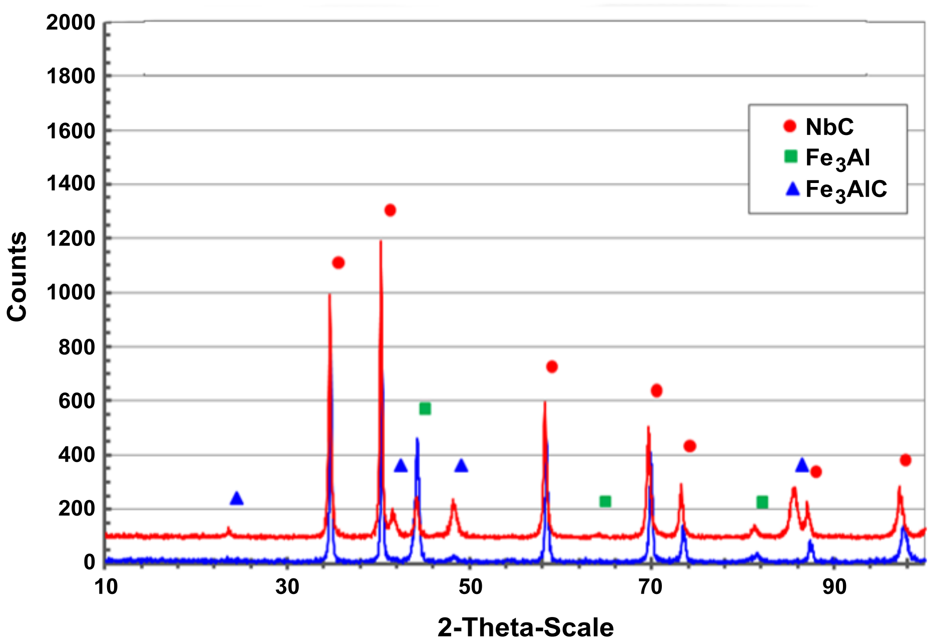


Figure 3. Main phases found in FeNbC [8].

The ranges of chemical composition and density of FeNbC are indicated in Table II. In addition to iron, niobium and carbon, other minor elements such as aluminum, manganese, silicon and titanium are found.

Table II. Range of Chemical Composition and Density of FeNbC

Fe	**Nb (wt.%)**	**C (wt.%)**	**Others**	**Density (g/cm^3)**
Base	30-60	4-8	Al, Ti, Mn, Si	6-7

Dissolution of FeNbC in Iron-Based Alloys

In order to determine the best dissolution practices of FeNbC in iron-based alloys for castings, the following methods of addition were tested: (a) simple dumping on the bath surface, SD, (b) melting down together with the metallic charge, MC, and (c) addition to the metal stream during ladle tapping, MS, Figure 4.

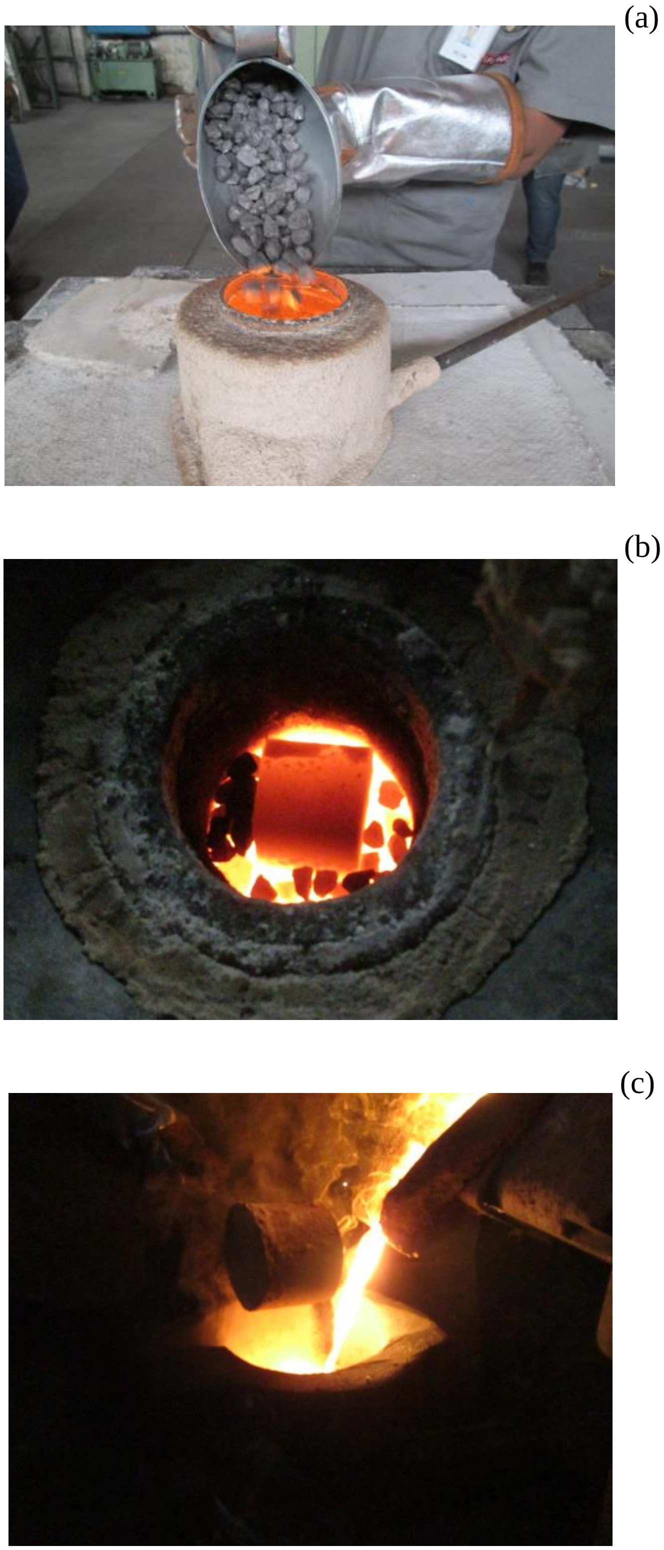


Figure 4. Methods of addition of FeNbC in iron castings: simple dumping on the surface (a), melting down with the charge (b) and addition to the metal stream during tapping (c).

As shown in Table III, the first set of trials (1 to 15) were conducted by simple dumping of FeNbC on the metal bath surface and the second set (16 to 30) by melting it together with the metallic charge. In both cases, increasing quantities of FeNbC particles with increasing size ranges from 0 to 1 mm, 1 to 6 mm, 6 to 12 mm, 12 to 25 mm and 25 to 50 mm were added, to determine the effect of the mass and the particle size on the dissolution and dispersion rates of NbC in the metal bath.

Table III. Experimental Conditions of the FeNbC Addition Trials Carried Out by Simple Dumping on the Bath surface (SD) and by Melting with the Metallic Charge (MC)

Trial (No)	**Particle Size (mm)**	**Nb Target (wt.%)**	**NbC Target (wt.%)**	**Addition of FeNbC (Method)**
1	0-1	2.5	2.8	Simple Dumping on the Bath (SD)
2	1-6			
3	6-12			
4	12-25			
5	25-50			
6	0-1	5	5.6	
7	1-6			
8	6-12			
9	12-25			
10	25-50			
11	0-1	10	11.3	
12	1-6			
13	6-12			
14	12-25			
15	25-50			
16	0-1	2.5	2.8	Melting with the Metallic Charge (MC)
17	1-6			
18	6-12			
19	12-25			
20	25-50			
21	0-1	5	5.6	
22	1-6			
23	6-12			
24	12-25			
25	25-50			
26	0-1	10	11.3	
27	1-6			
28	6-12			
29	12-25			
30	25-50			

The trials were carried out in a laboratory induction furnace containing, before the addition, 12 to 14 kg of liquid indefinite chilled cast iron with 3.5 wt.%C, 1.1 wt.%Si, 4.2 wt.%Ni and 2.2 wt.%Cr. The liquid metal at about 1530 ºC was protected by argon shielding. The chemical composition of the FeNbC was approximately 46.2 wt.%Nb, 7.0 wt.%C, 3.8 wt.%Al, 0.5 wt.%Si and 0.04 wt.%Ti.

In the trials carried out by simple dumping on the metal bath, the total mass of FeNbC was added gradually in 3, 5 and 10 parts in order to obtain 2.8 wt.%, 5.6 wt.% and 11.3 wt.%NbC, respectively, while preventing the bath from cooling and freezing. After each addition, the liquid metal was manually stirred to promote the dissolution of the FeNbC particles and samples were taken by suction in quartz tubes to track the dissolution process by chemical analysis of the NbC content. Finally, the metal was tapped in a preheated ladle and cast in sand molds.

In the trials carried out by melting with the metallic charge, the whole mass of FeNbC particles with different size ranges was charged and melted down together with the solid charge. After adjusting the temperature to about 1530 ºC, the metal bath was intermittently manually stirred to promote the dissolution process. Samples of the liquid metal were taken by suction in quartz tubes for chemical analysis, as before. Finally, the metal was tapped.

The experimental conditions of the third and fourth sets of trials are shown in Table IV. Trials 31 to 33 were carried out by simple dumping of FeNbC on the metal stream during pouring to the tapping ladle, and trials 34 to 39 were conducted by simple dumping of FeNbC on the metal surface. Increasing amounts of FeNbC with different particle size ranges (0 to 1 mm and 12 to 25 mm) to obtain 2.8 wt.%, 5.6 wt.% and 11.3 wt.%NbC in the metal bath were added, aiming at determining the effect of the mass and particle size on the FeNbC dissolution rate. The trials were carried out in an induction furnace containing from 40 to 47 kg of molten indefinite chilled cast iron with 3.5 wt.%C, 1.1 wt.%Si, 4.2 wt.%Ni and 2.2 wt.%Cr.

Table IV. Experimental Conditions of FeNbC Dissolution Trials carried out by Simple Dumping on the Metal Stream during Tapping (MS) and on the Metal Bath Surface in the Furnace (SD)

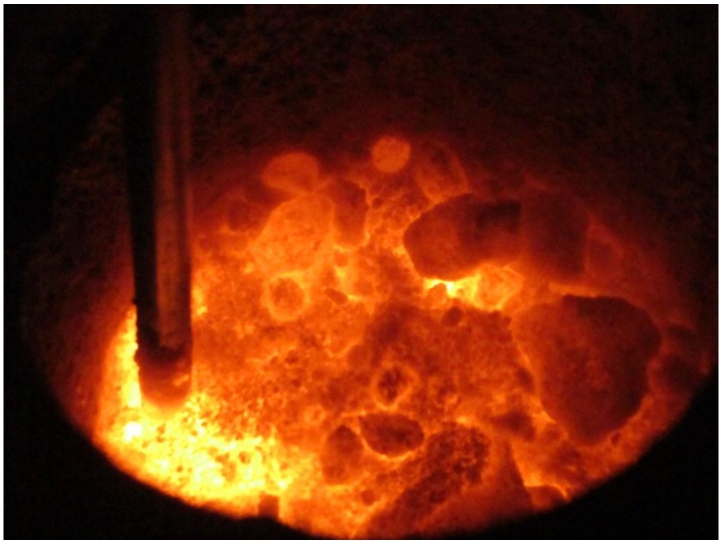
Trial (No)	**Particle Size (mm)**	**Nb Target (wt.%)**	**NbC Target (wt.%)**	**Addition of FeNbC (Method)**
31	0-1	2.5	2.8	Dumping on the Metal Stream (MS)
32	0-1	5	5.6	
33	0-1	10	11.3	
34	0-1	2.5	2.8	Simple Dumping on the Bath (SD)
35	12-25			
36	0-1	5	5.6	
37	12-25			
38	0-1	10	11.3	
39	12-25			

In the simple dumping trials, the temperature of the metal bath was adjusted to 1530 ºC before the addition of the particles. The total mass of FeNbC was added gradually in 3, 5 and 10 parts in order to obtain 2.8 wt.%, 5.6 wt.% and 11.3 wt.%NbC, respectively, while preventing the bath from cooling and freezing. To promote the dissolution of the FeNbC particles, the liquid metal was manually stirred after each addition. Samples of liquid metal were taken during the process and the bath was protected by argon shielding.

In the dissolution trials from the addition of FeNbC particles in the metal stream, only fine particles (<1 mm) were added during the pouring of the liquid metal to the tapping ladle. The bath temperature was adjusted in the induction furnace to 1600 ºC in order to compensate for the heat losses in the preheated ladle. After the addition of FeNbC to the stream, the metal bath was manually stirred in the ladle to promote the dissolution of the fine FeNbC particles floating on the surface. Samples of liquid metal were taken by suction in quartz tubes to determine the increase in NbC content as a function of time and then the metal was tapped.

Results

In the dissolution trials using simple dumping, the finer particles (<6 mm) showed a tendency to keep floating, undissolved, on the bath surface even after manual stirring. On the other hand, the coarser particles (>6 mm) sank almost immediately into the bath, leading quickly to a clean surface bath appearance, indicative of a faster dissolution process, Figure 5. Similar behavior was observed in the dissolution trials carried out by melting with the metallic charge, where the finer particles floated to the bath surface after stirring while the coarser particles remained submerged in the molten metal.



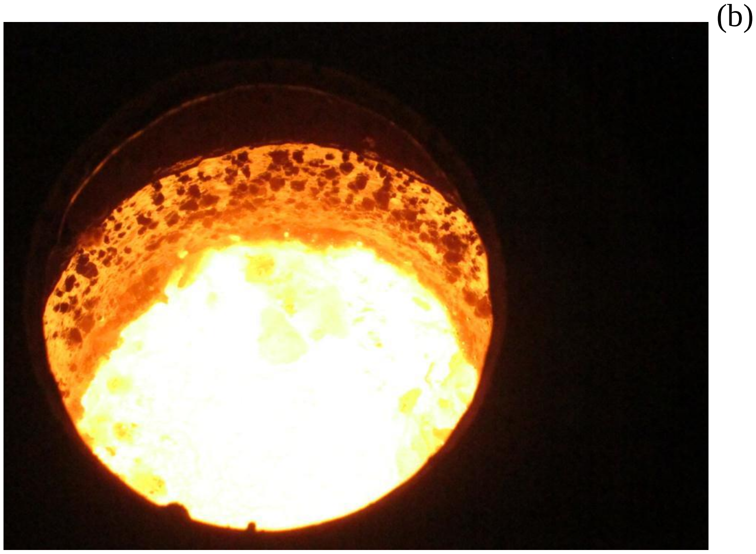
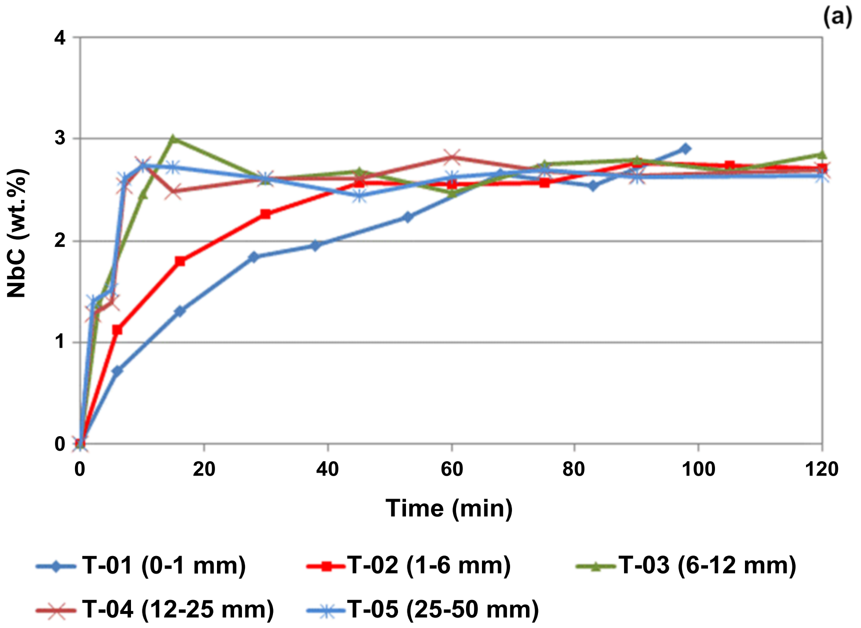


Figure 5. Appearance of the metal surface after the dissolution of FeNbC aiming to obtain 11.3 wt.%NbC. Fine particles (<1 mm) (a) and coarse particles (12-25 mm) (b).

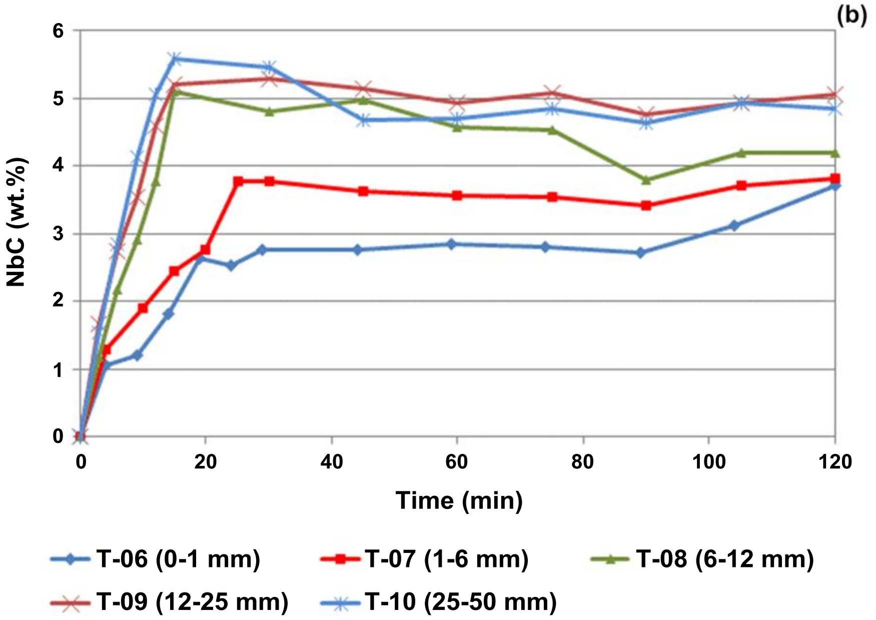
Figure 6 displays the experimental results of the NbC content in the metal phase as a function of time from the dissolution trials of different particles sizes of FeNbC by simple dumping on the bath and by melting with the charge.

In the trials carried out by simple dumping, the total time (120 minutes) included the period for the addition of the FeNbC particles on the bath surface, in addition to the time spent for their dissolution at 1530 ºC, Figures 6(a), (b) and (c). In the trials carried out by melting with the metallic charge, the total time (120 minutes) comprised the periods for heating, melting and holding the bath at 1530 ºC for dissolution and sampling, Figures 6(d), (e) and (f).

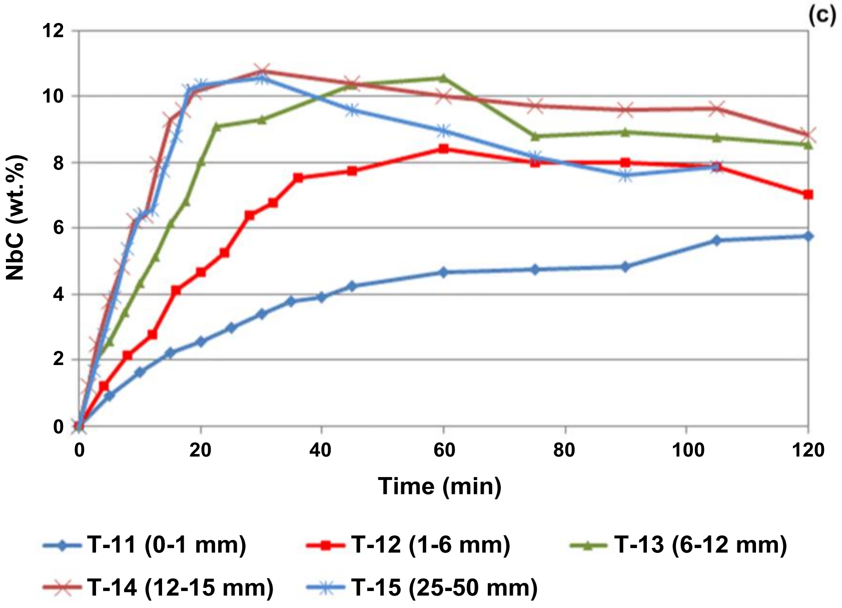
In the dissolution trials carried out by simple dumping of FeNbC on the bath, coarser particles (>6 mm) dissolved faster and more effectively than the finer ones (<6 mm), reaching NbC contents equal, or very close to, the target values (2.8 wt.%, 5.6 wt.% and 11.3 wt.%) in less than 30 minutes, Figures 6(a), (b) and (c). The addition of the finer particles (<6 mm) led to NbC contents close to the target values only for the lowest NbC concentration (2.8 wt.%).



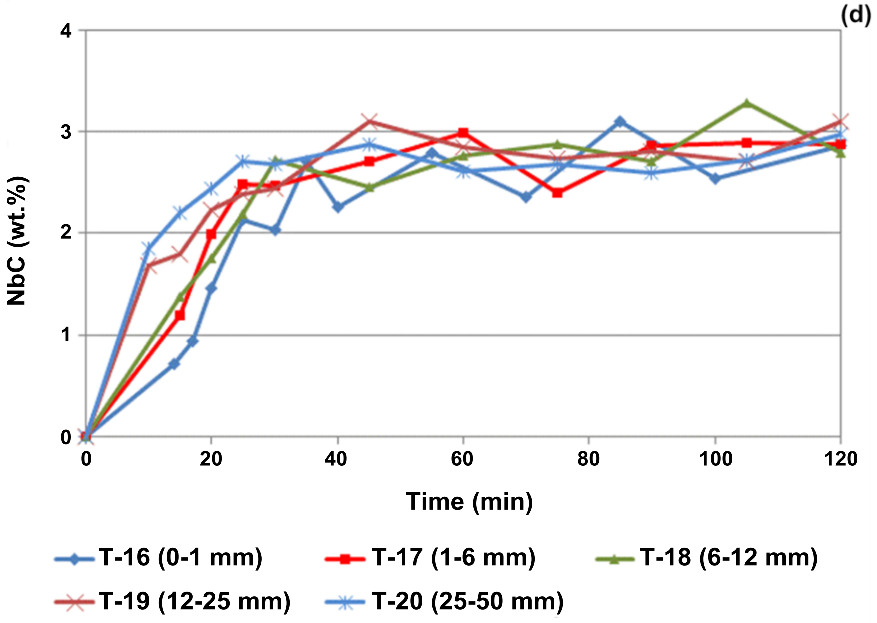
SD: 2.8 wt.%NbC



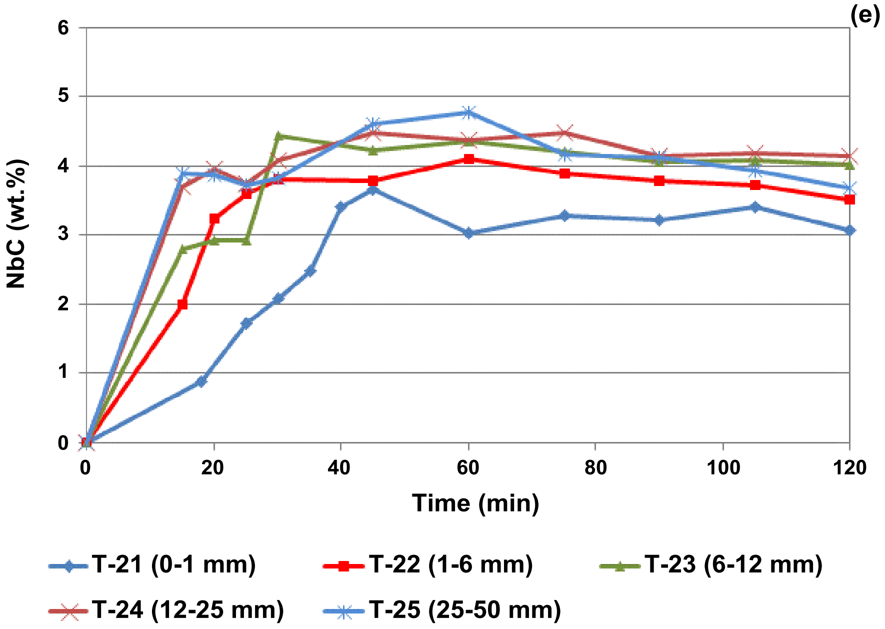
SD: 5.6 wt.%NbC



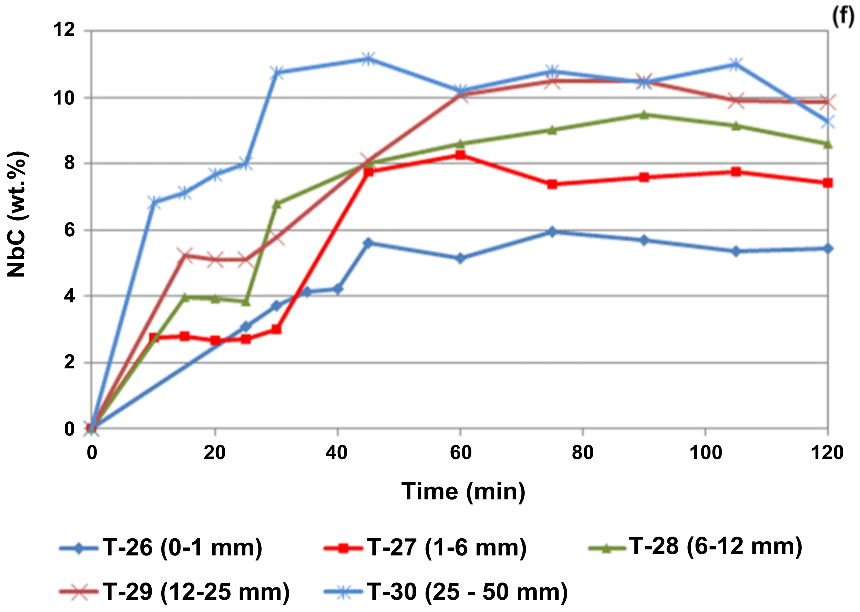
SD: 11.3 wt.%NbC



MC: 2.8 wt.%NbC



MC: 5.6 wt.%NbC



MC: 11.3 wt.%NbC

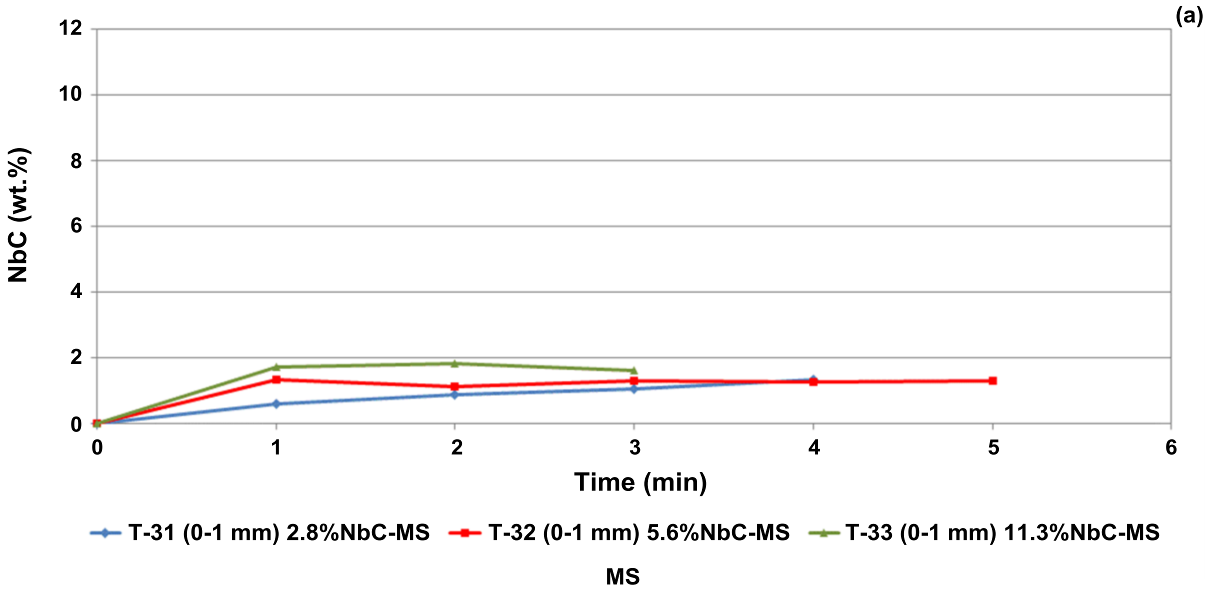
Figure 6. NbC content as a function of time. Addition of FeNbC with different particle sizes by simple dumping (SD) on the bath (a, b and c) and by melting with the charge (MC), (d, e and f).

The lower dissolution rate seen for the finer material is related to the fact that although having a larger surface area than the coarser material, the finer material agglomerated and remained undissolved floating on the bath surface, offering a smaller effective contact area for the dissolution reaction with the molten metal, Figure 5(a). Meanwhile, the coarser particles that remained totally submerged just after their addition to the metal bath presented an effectively larger contact area for the dissolution reaction in the liquid metal.

Figures 6 (d), (e) and (f) show that the results from the dissolution trials conducted by melting the FeNbC particles together with the metallic charge were very similar to those obtained in the dissolution trials carried out by simple dumping on the bath. However, in this MC process the dissolution of the finer particles (<6 mm) was improved during the melting process due to their closer and longer contact within the bath with all the particles remaining submerged in the liquid metal.

Both methods of adding FeNbC – simple dumping on the bath surface or melting down together with the metallic charge – were very effective for dissolving FeNbC particles in the bath with a slight advantage for finer particles when they were melted down together with the charge, as shown in Figure 6.

The results of the dissolution trials of FeNbC by simple dumping in the metal stream (MS) compared to simple dumping on the bath surface (SD) are shown in Figures 7(a) and (b) in terms of the NbC content of the metal phase as a function of time.



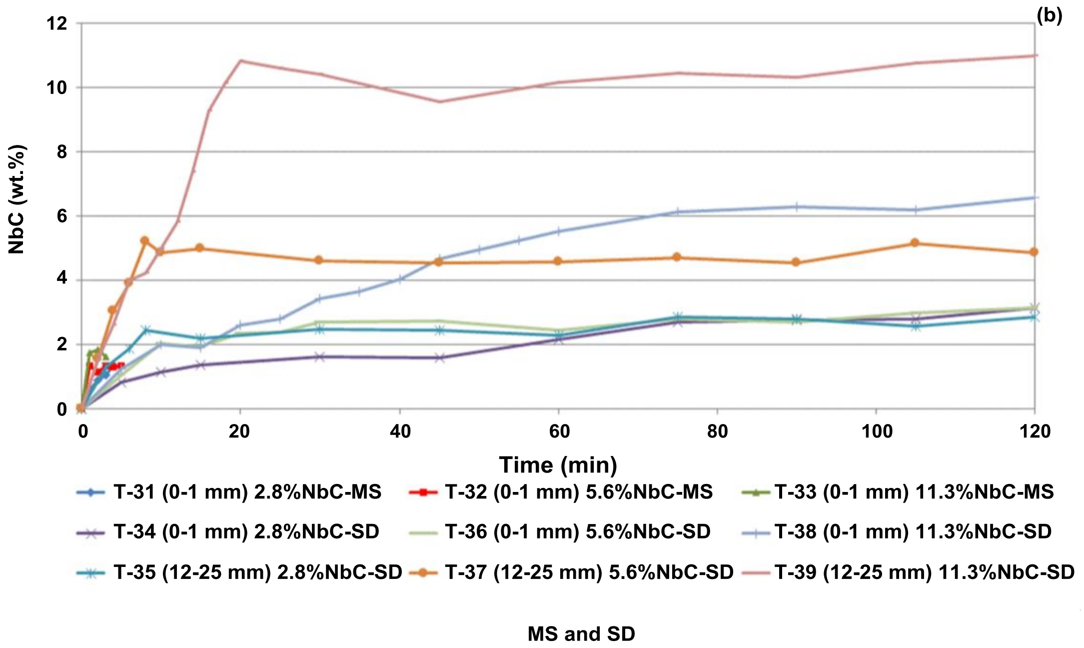
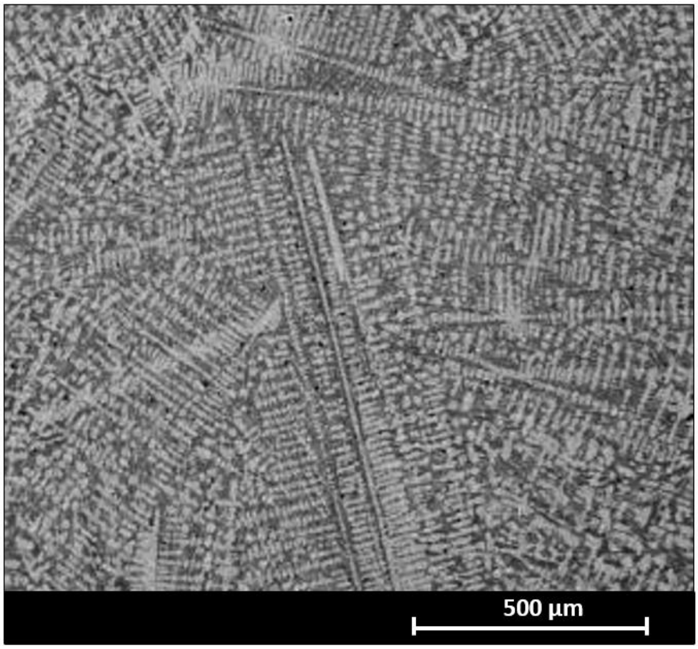


Figure 7. NbC content as a function of time. Addition of FeNbC by simple dumping on the metal stream (MS) during tapping (a) and compared to simple dumping on the metal bath (SD) in the furnace (b).

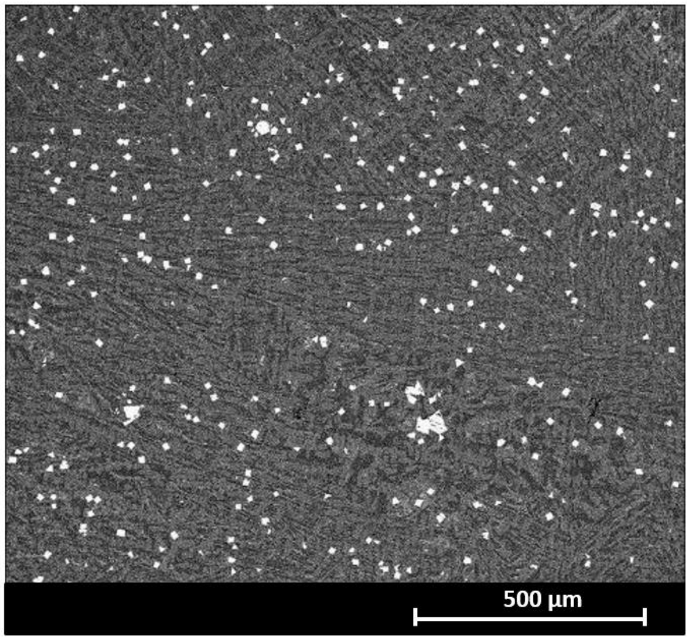
In the dissolution trials of FeNbC carried out by simple dumping in the metal stream, in spite of the good mixing between the particles and the falling stream, most of the fine material floated to the bath surface hindering its dissolution, mainly when high NbC contents were sought. As a result, Figure 7(a) shows that the addition of fine particles (<1 mm) added to the metal stream during pouring into the tapping ladle led to very low NbC contents in the metal phase for all the targeted NbC values. The poor dissolution was attributed to the short period available for dissolution during pouring, to the high drop in temperature of the liquid metal in the ladle and to the tendency of the fine material to float and agglomerate on the bath surface. On the other hand, it was observed that the addition of the same fine particles (<1 mm) by simple dumping on the metal surface led to higher NbC contents in the metal phase for all the targeted NbC contents, Figure 7(b). However, the addition of coarser particles (from 12 to 25 mm) by simple dumping on the metal surface resulted in NbC contents still higher than those achieved with the fine material (<1 mm). Those higher values were very close to the targeted contents (2.8 wt.%, 5.6 wt.% and 11.3 wt.%NbC) and confirmed the results achieved in the first set of trials carried out under similar experimental conditions, Figure 6(a) to (c).

Figure 8 shows the results of the microstructural analysis via SEM/EDS of indefinite chilled cast iron samples obtained after the dissolution trials of FeNbC aimed at producing a range of NbC contents (2.8 wt.%, 5.6 wt.% and 11.3 wt.%).

(a)



(b)



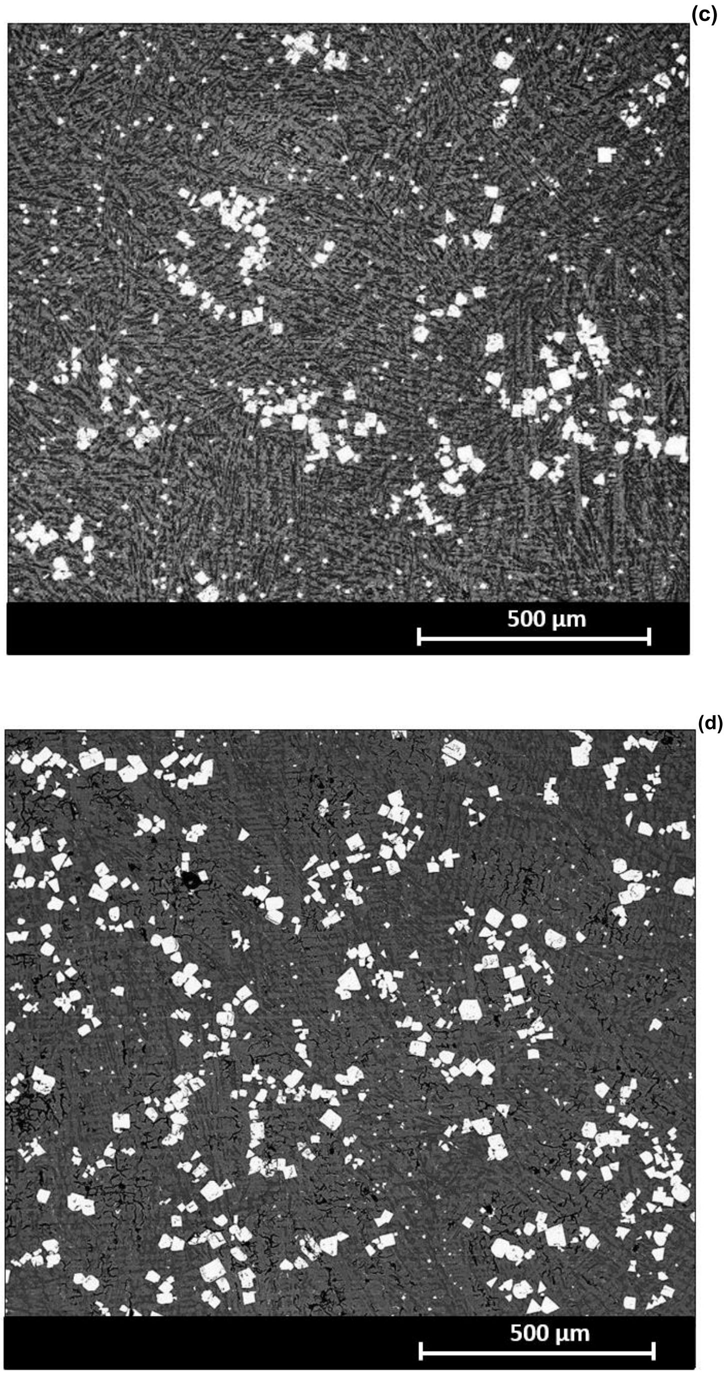


Figure 8. Microstructure (SEM/EDS) of an indefinite chilled cast iron before and after the dissolution of FeNbC from 12 to 25 mm.
(a) 0 wt.%NbC, (b) 2.8 wt%NbC, (c) 5.6 wt.%NbC, (d) 11.3 wt.%NbC.

The increase in the quantity of FeNbC added to the indefinite chilled cast iron resulted in microstructures with increasing volume fractions of hard primary NbC (white phases seen in the micrographs), Figures 8(b) to (d). Since the density of NbC is similar to the melted cast iron and likewise most of the iron alloys, the particles of NbC coming from the dissolution of the FeNbC matrix were spread out over the microstructure of the cast iron. It was observed that the higher the NbC content, the higher the tendency of the fine particles to coarsen and form bigger NbC particles. It seems also that the insertion of NbC, through the dissolution of the iron-aluminide matrix of FeNbC, led to finer as-cast microstructures than those obtained without the addition of niobium. In fact, as seen in Figure 8(a), the structure of the indefinite chilled cast iron without NbC is much coarser than the structures of the cast iron with increasing NbC contents, Figure 8(b) to (d).

Based on the experimental results, it is clear that the use of FeNbC enables the development of different wear resistant cast irons or steels containing high levels of hard primary NbC dispersed in the host metal matrix, which could be suitable for diverse applications in the mining and processing industry.

Conclusions

The properties and dissolution of FeNbC in iron-based alloys were investigated, aiming at developing wear resistant materials containing high contents of hard NbC. The dissolution trials were carried out by the addition of FeNbC in cast iron melted in laboratory induction furnaces. Three methods of addition were examined: dumping on the melt surface, melting down with the metal charge and adding to the metal stream during tapping.

The following conclusions were drawn:

1. FeNbC is a metal matrix composite that contains 40 to 80% of hard NbC homogeneously distributed in an iron-based matrix, with residual levels of aluminum, silicon and manganese.

2. Melting with the metallic charge was the most efficient method of dissolving FeNbC in the metal bath. The second most efficient method was by simple dumping on the metal surface.

3. The addition of FeNbC particles to the liquid metal stream during pouring showed the lowest dissolution rates.

4. Coarse FeNbC particles (>6 mm) dissolved faster and more effectively than the finer material since small particles tend to float and agglomerate, remaining undissolved on the bath surface.

5. Hard NbC particles from the dissolution of the FeNbC matrix were evenly dispersed within the iron alloy casts due to the similar densities of NbC and the liquid iron alloys. Thus, the dissolution of FeNbC enables the development of different wear resistant cast irons or steels with high contents of hard primary NbC suitable for diverse applications in the mining and processing industries.

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