ISSN : 0974 - 7486 Volume 14 Issue 11

Materials Science

An Indian Journal

Full Paper

MSAIJ, 14(11), 2016 [448-455]

# Test of elaboration protocols for obtaining highly Co- or Ni -alloyed spheroidal cast irons from an industrial SG cast iron. Part E: Synthesis of all results and analysis of the Ni and Co contents on microstructures and properties

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## ABSTRACT

In this final paper one summarized all the obtained results concerning the "xM(1-x)FGS" cast irons (M=Ni, Co or pure Fe, x=0.25, 0.50 and 0.75), issued from the previous articles of this series. Microstructures (graphite, matrix) and mechanical properties (hardness, yield strength and hardening in compression) are gathered to be analysed versus the nature of the M element at constant M content and versus the M content at constant M nature. The most established laws concern microstructure. First interpretations are given about the effects of Ni and Co on the graphite morphology and on the matrix nature. Outlooks to deepen the understanding and enriching this knowledge are proposed. 

## KEYWORDS

Spheroidal graphite cast iron;
Nickel;
Cobalt;
Microstructure;
Compression properties;
Hardness;

## INTRODUCTION

Cast irons, first product obtained from iron ore by reduction of hematite in blast furnace may present extremely various microstructures even with simple chemical compositions made of Fe, C and Si: white cast irons, grey cast irons (with flake, vermicular or spheroidal graphite, various fineness and distribution), ferrite, ferrite-pearlite, pearlite (lamellar more or less fine, globular), high bainite, low bainite, martensite…[1-3]. They may be less or more highly alloyed with other elements Ni, Mo, Cr, P… to achieve specific sets of properties. Some of these elements can be met in particularly high amounts such as nickel[4,5]. Some alloyed cast irons are able to be used at high temperature by exploiting their high temperature stability[6], high thermal conductivity[7], low thermal expansion coefficient[8,9] or mechanical strength[10] for example. Many other alloyed cast irons may lead to interesting mechanical properties at room temperature, whatever the mode of solicitation[11-17]. Wear resistance[18-20] as well as resistance against oxidation and corrosion[21-23] are also properties that some cast irons may bring, as the chromium-containing versions[24-26] for example. Combination of wear and corrosion in erosion-inducing applications[27] can be also answered by cast irons.

Among the highly alloyed cast irons the Spheroidal Graphite (SG) cast irons play a particularly important role since they compete with alloyed steels. Nickel is maybe the most frequent alloying element which can be met in alloyed cast-iron. In the series of articles preceding this synthesizing-concluding one, we explore the possibilities of elaborating less or more highly alloyed SG cast iron by simple re-melting of a pre-elaborated SG cast iron by mixing it with mother Ni-carrier – and also Co-carrier – synthetic cast iron by expecting to benefit from the spheroidisation and inoculation treatments which were initially applied to liquid metal for obtaining the original SG cast iron (industrial origin). These alloys were all microstructurally characterized and some of their mechanical properties (compression, hardness) specified. The aim of the present final article is to collect and gather the obtained results to extract general knowledge.

## EXPERIMENTAL

### Elaboration of the alloys

One can remind that the studied cast irons were all elaborated by melting together 30, 20 or 10g of the industrial SG cast iron (Fe-3.5C-2.5Si+trace elements, wt.%) and 10, 20 or 30g (respectively) of another charge. This one was either a mix of pure elements directly melted with the SG cast iron parts (1$^{st}$ protocol [28]), or a real mother alloy of composition Ni-3.5C-2.5Si or Co-3.5C-2.5Si (second protocol[29]). Additional cast irons in which pure Fe replaced pure Ni or pure Co were also elaborated, for comparison.

### Metallographic observations

After cutting for obtaining parts for the metallography work and parallelepipeds for the compression tests, the parts of the first type were embedded in a cold resin mixture, ground, polished until mirror-like state of the sample surface, the observed. Observation were done using an optical microscope before and after etching by Nital4, and also using a Scanning Electron Microscope in Back Scattered mode, with its Energy Dispersion Spectrometry device to control the obtained chemical compositions and to specify the composition of matrix by spot analysis.

### Compression tests

An electromechanical uniaxial testing machine equipped with compression platens was used to acquire strain-stress curves in most cases beyond the yield strength and in rare cases until rupture.

### Density estimation

Accurately weighed and dimensionally measured the volume mass of all the samples, before and after compression, were calculated.

### Hardness measurements

The mounted samples and the not mounted samples deformed by compression were subjected to Vickers indentation to value their hardness.

## RESULTS AND DISCUSSION

The targeted compositions of all the studied cast irons are reminded in TABLE 1 while TABLE 2 recalls the details of the charges prepared for the elaborations.

The general microstructures of the obtained cast irons are reminded in Figure 1 for the "50Ni50FGS", "50Co50FGS" and the control alloy "50Fe50FGS" by optical micrographs taken of etched samples: the ones entitled "1$^{st}$ protocol" were generally flake graphite cast irons although that some degenerated spheroids can be seen in the "50Co50FGS" cast iron and in the "50Fe50FGS" one, only for the second protocol. Concerning matrix the one of the "50Ni50FGS" cast iron is metallic (probably austenitic thanks to the high content in Ni). The one of the "50Co50FGS" cast iron seems essentially ferritic despite some pearlitic areas are also present. The "50Fe50FGS" is rich in ledeburite, consequence of the fall of solidification in the metastable austenite-cementite phase diagram.

**TABLE 1 : Reminder of the targeted chemical compositions**

| Alloys | Fe | Co | Ni | C | Si |
|---|---|---|---|---|---|
| | M = Fe alloys | | | | |
| « NiFe » | 47 | / | 47 | 3.5 | 2.5 |
| « CoFe » | 47 | 47 | / | 3.5 | 2.5 |
| « FeFe » | 47+47 | / | / | 3.5 | 2.5 |
| | M = 1/3 Fe alloys | | | | |
| « 25Ni75FGS » | 70.5 | / | 23.5 | 3.5 | 2.5 |
| « 25Co75FGS » | 70.5 | 23.5 | / | 3.5 | 2.5 |
| « 25Fe75FGS » | 23.5+70.5 | / | / | 3.5 | 2.5 |
| | M = 3 Fe alloys | | | | |
| « 75Fe25FGS » | 23.5 | / | 70.5 | 3.5 | 2.5 |
| « 75Co25FGS » | 23.5 | 70.5 | / | 3.5 | 2.5 |
| « 75Fe25FGS » | 70.5+23.5 | / | / | 3.5 | 2.5 |

**TABLE 2 : Reminder of the prepared charges before melting**

| Alloys | FGS | Ni | Fe | Co | C | Si |
|---|---|---|---|---|---|---|
| | | | M = Fe alloys | | | |
| « NiFe » | 20.120 | 18.797 | / | / | 0.693 | 0.507 |
| « CoFe » | 20.186 | / | / | 18.802 | 0.701 | 0.519 |
| « FeFe » | 20.260 | / | 18.670 | / | 0.740 | 0.520 |
| | | | M = 1/3 Fe alloys | | | |
| « 25Ni75FGS » | 30.145 | 9.420 | / | / | 0.341 | 0.25 |
| « 25Co75FGS » | 30.089 | / | / | 9.40 | 0.35 | 0.27 |
| « 25Fe75FGS » | 30.123 | / | 9.413 | / | 0.340 | 0.247 |
| | | | M = 3 Fe alloys | | | |
| « 75Fe25FGS » | 10.149 | 28.260 | / | / | 1.05 | 0.75 |
| « 75Co25FGS » | 10.330 | / | / | 28.215 | 1.055 | 0.759 |
| « 75Fe25FGS » | 10.40 | / | 28.30 | / | 1.059 | 0.753 |

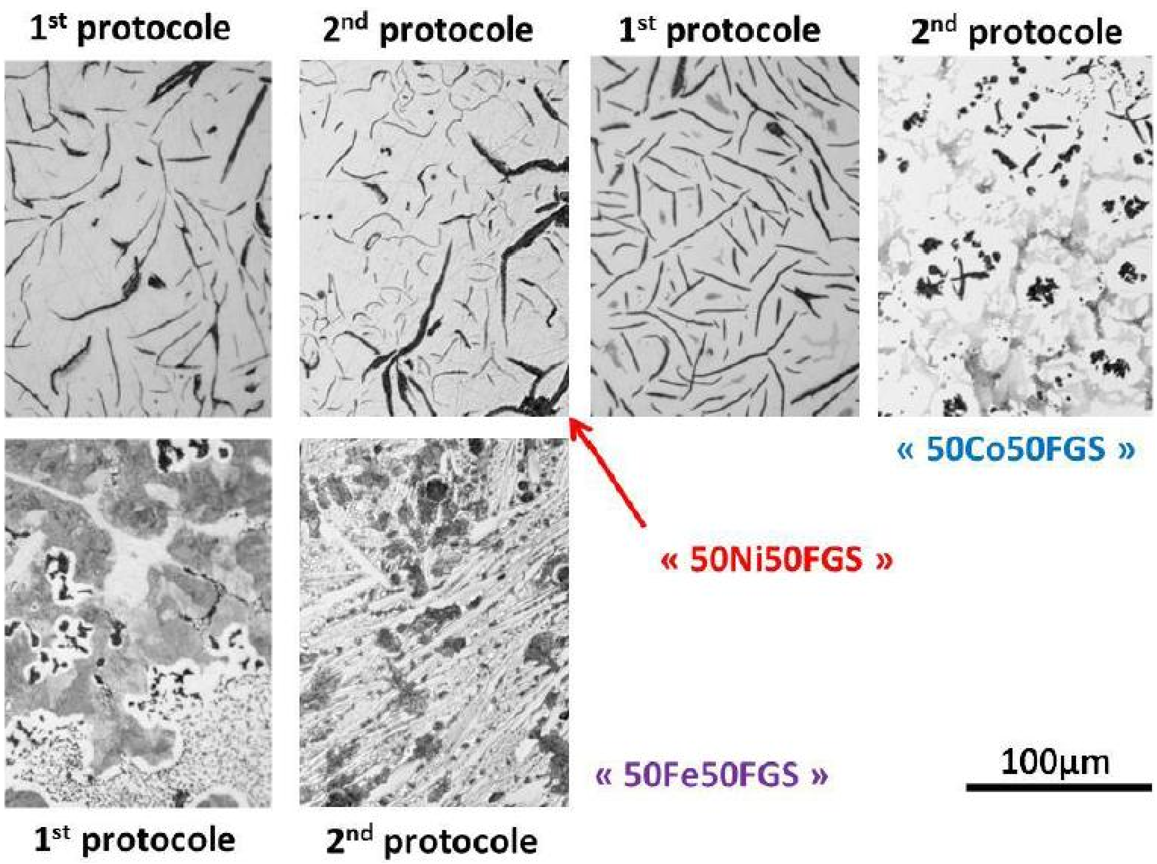


**Figure 1 : Microstructures of the "50M50FGS" cast irons (optical micrographs after Nital etching)**

The optical micrographs presented in TABLE 2 remind the microstructures of the three "25M75FGS" cast irons after Nital etching. Graphite is globally (but more or less depending on the added element, Ni, Co or Fe) spheroidal. Pearlite is very present in the "25Co75FGS" cast iron (much than for 50wt.%Co) and a little pearlite (?) is present in the "25Ni75FGS"cast iron (totally absent when 50wt.%Ni).

The "25Fe75FGS" cast iron looks like hypo-eutectic white cast iron however with some graphite nodules.

The microstructures of the "75M25FGS" cast irons are recalled in Figure 3. The matrix seem being not etched by Nital (the "75Fe25FGS" too) and graphite is essentially lamellar. Among the numerous graphite lamellae some rare isolated degenerated graphite nodules

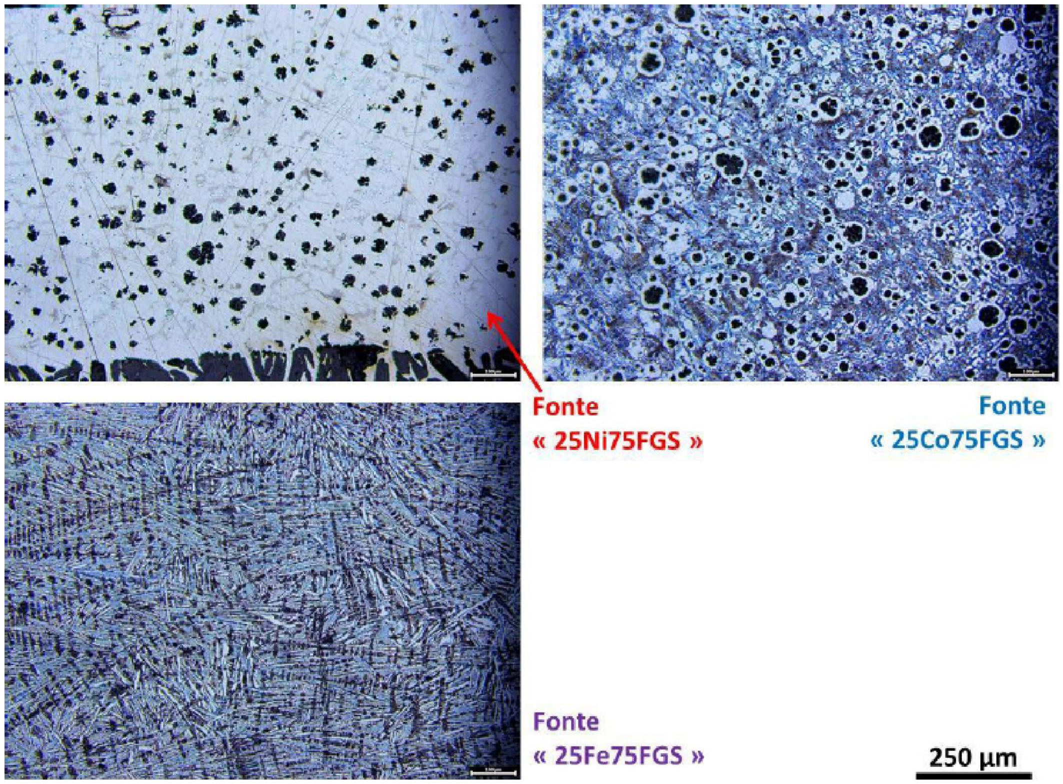


**Figure 2 : Microstructures of the "25M75FGS" cast irons (optical micrographs after Nital etching)**

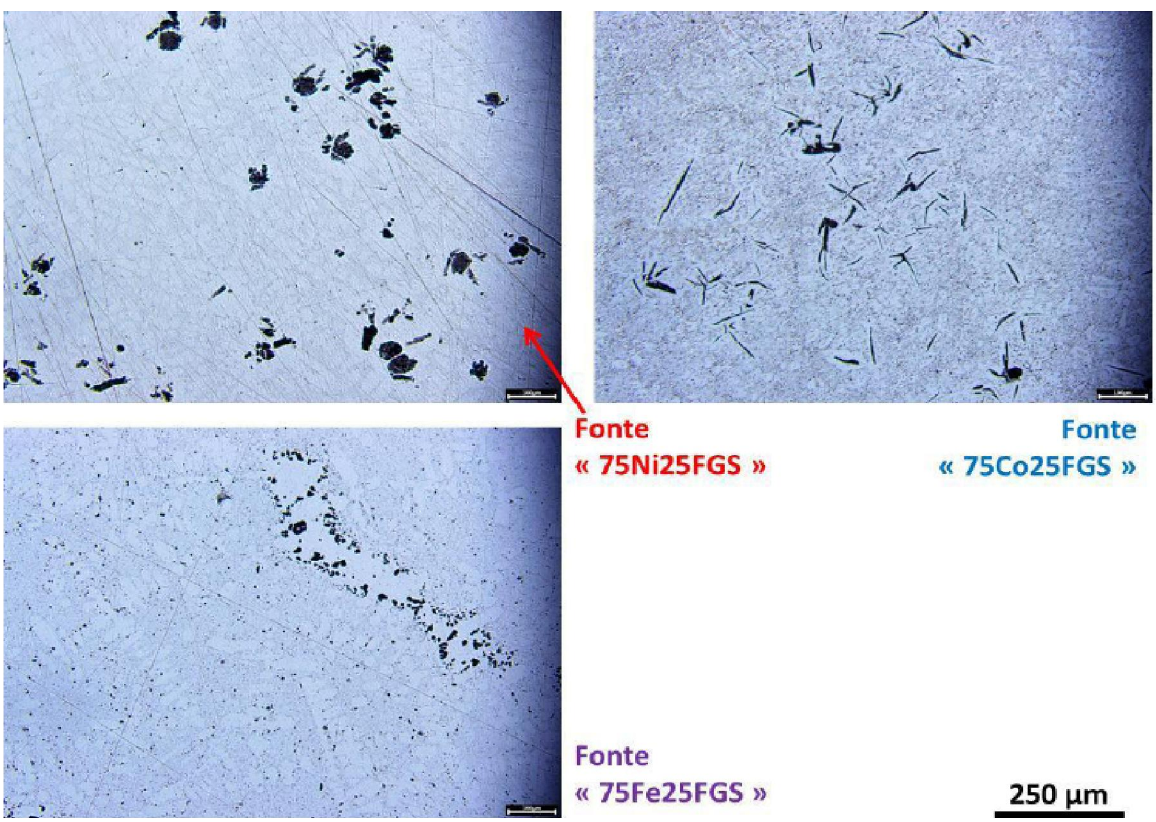


**Figure 3 : Microstructures of the "75M25FGS" cast irons (optical micrographs after Nital etching)**

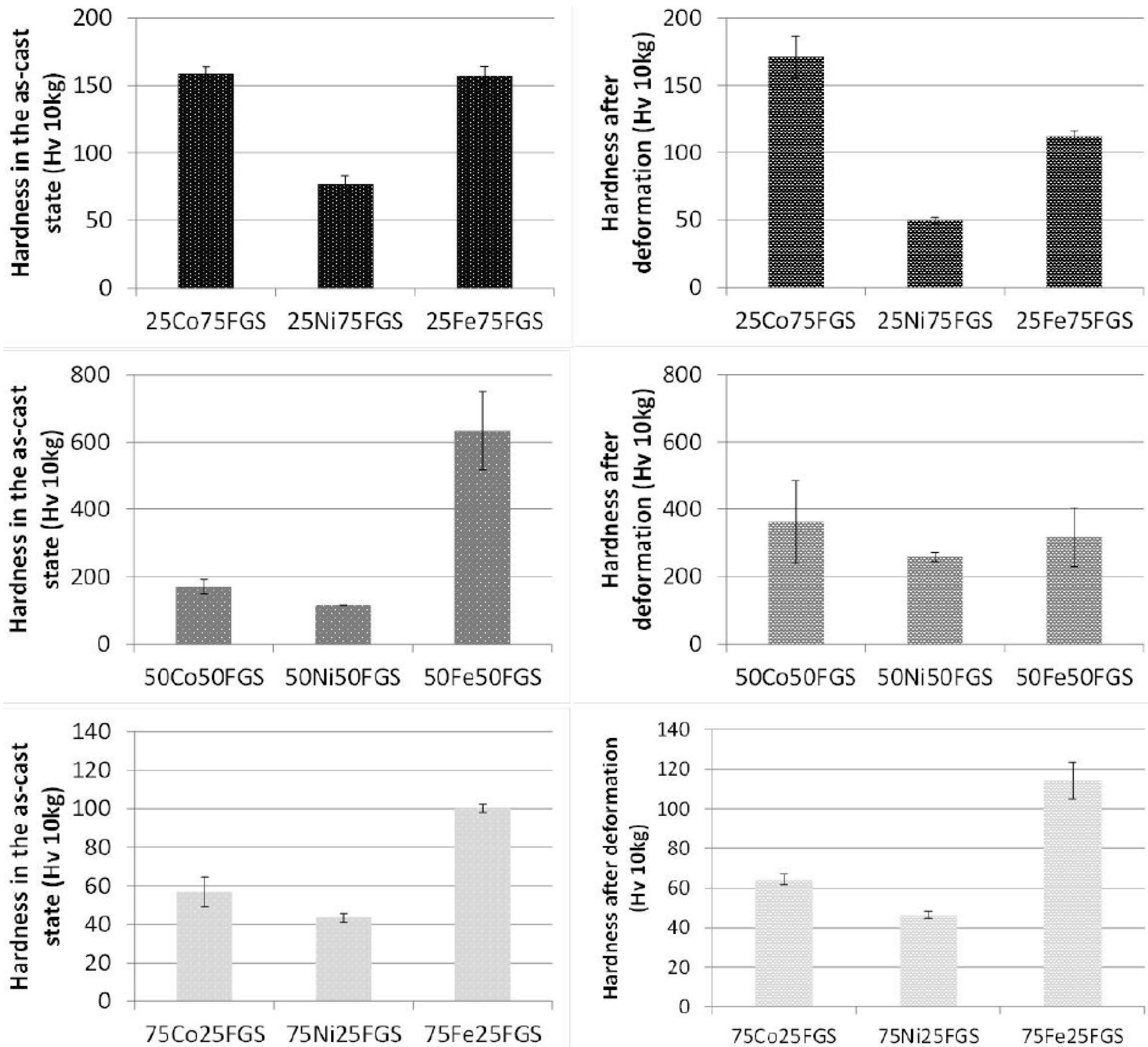


**Figure 4: Hardness of the nine cast irons in the as-cast state (left) and in the plastically compressed state (right)**

or coarse graphite plates are also present.

The indentation results are graphically given in Figure 4. One can see that, globally, the “xFeyFGS” cast irons are the hardest alloys in all cases, this being attributed to the general presence of ledeburite, although that this compounds was not revealed by Nital in the “75Fe25FGS” cast iron. In all cases again, the “xNiyFGS” cast irons were the softest ones, this being due to the intrinsic relative softness of nickel by comparison to cobalt and to iron alloys containing carbides in significant part.

The strain-stress curves, the elastic part of which has been removed, are gathered by the nature of the M element in the “xMyFGS” cast irons (Figure 5). This graphically shows that the increase in Ni led to higher yield stress while the conclusions are unfortunately not so clear concerning the effects of the addition in Co and in pure Fe: the results (yield strength, hardening) are rather scattered without monotonous relation with the addition of Co and pure Fe.

## General commentaries

The previous observations and results are summarized in TABLE 3, in which one can observe that the graphite type is clearly dependent on the content in add M element: the higher this one is, the less nodular graphite is. The transition spheroidal ’! lamellar occurs sooner for nickel than for cobalt, and sooner for cobalt sooner than for iron. Since, for the same elaboration protocol, graphite was really nodular in eth “xFeyFGS”

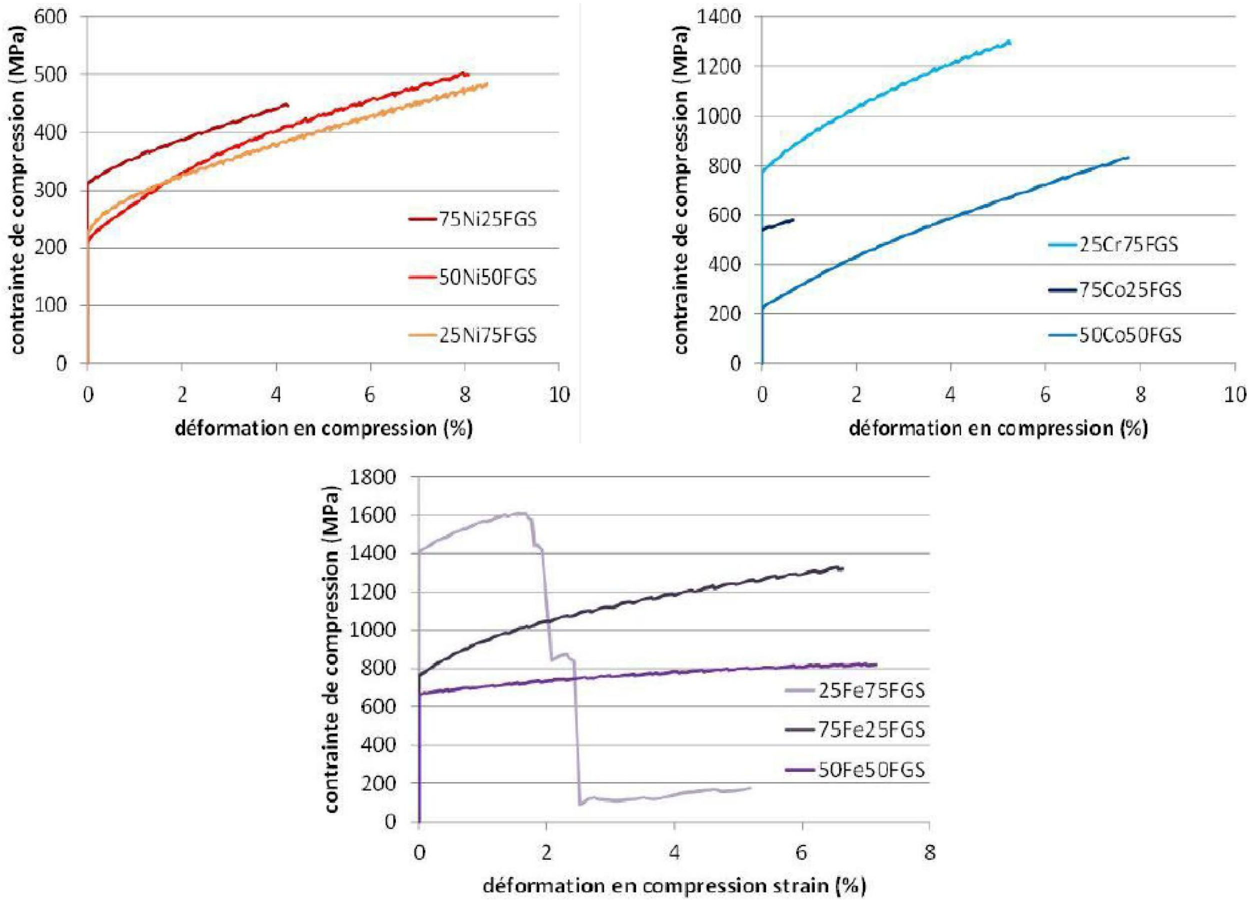


**Figure 5 : Effect of the contents in M element (added according to the protocol 2) on the plastic part of the compression strain-stress curves (elastic part removed)**

**TABLE 3 : Synthesis of all the microstructure and mechanical properties results**

| M | Graph/MATRIX | 25M75FGS | 50M50FGS | 75M25FGS |
|---|---|---|---|---|
| Ni | graphite | NODULAR | Lamellae + plates + nodules | Nodules + lamellae + plates |
| | MATRIX | Almost changed by Nital etching | Not changed by Nital etching | Not changed by Nital etching |
| | Hardness (Hv10kg) | *77 ±6* | 115 ±1 | 44 ±2 |
| | Yield strength (MPa) | 225* | 208 | 311 |
| Co | graphite | NODULAR | Rosettes + some nodules | Rosettes + some nodules |
| | MATRIX | Ferrite-Pearlite (« Bull's eyes ») | Ferrite-Pearlite (« Bull's eyes ») | Not changed by Nital etching |
| | Hardness (Hv10kg) | 159 ±5 | 171 ±21 | 58 ±8 |
| | Yield strength (MPa) | 772* | 225 | 539 |
| Fe | graphite | NODULAR | NODULAR | Small nodules + very short lamellae |
| | MATRIX | Ledeburite and Pearlite | Ledeburite and Perlite | Not changed by Nital etching |
| | Hardness (Hv10kg) | 157 ±7 | 633 ±116 | 100 ±2 |
| | Yield strength (MPa) | 1405* | 658 | 763 |

**(*: compression results obtained for the cast irons of the same compositions but issued from the first protocole, as is to say with lamellar graphite)**

cast iron at least until x reaches 50%, it seems that graphite tends to be degenerated by Co and by Ni one can think that these elements slightly acts as poisons for spheroidal graphite, but much less stronger than sulphur: about 50 wt.% of Co and between 25 and 50 wt.% of Ni deteriorate spheroidal graphite much less than 0.01 wt.% of sulphur.

Concerning the matrix, it was clear that substituting 25wt.%Ni or 25wt.%Co or more to Fe leads to a solidification in the austenite-graphite stable Fe-C diagram, differently to what occurred, for the same thermal conditions of cooling, for the "xFeyFGS" cast irons which led to many ledeburite. With 25wt.%Ni or more, the matrix probably remains austenitic, influenced by the face centred cubic structure of pure nickel, which did not know eutectoid transformation when rapid cooling to low temperatures. In contrast, cobalt did not obstruct the eutectoid transformation into pearlite. Seemingly only 75wt.%Co favoured the stability of a metallic matrix.

Concerning the effect of the family type on the mechanical properties it seems that globally Co leads to higher hardness and higher yield strength than Ni, this being partly due to the ferrite-pearlitic structure that Ni obstructed ('! rather soft matrix) while Co did not do that ('! rather hard matrix). Beside this indirect effect of Co there is obviously also a direct effect since the 75Co25FGS cast iron (metallic matrix) is harder than the 75Ni25FGS one (metallic matrix too). It was not possible to also compare with iron since, at least the 25Fe75FGS and 50Fe50FGS cast irons, are drastically harder and stiff because of the ledeburite they contain.

In contrast, unfortunately, concerning the dependence of the mechanical properties (hardness, yield strength, hardening) on the content of the added element, the results are too scattered to give any rule. Worse, the variations are not monotonous. Additional work must be done to hope revealing clear dependence.

## CONCLUSION

In this final paper, one took again all the results and gathered/classified them. There are some effects of the presence of nickel or cobalt in so high contents on both microstructures and selected mechanical properties. If the influences on microstructure were globally well identified, this is totally not the case for the mechanical properties. It will be possible in additional work to prepare new "xM(1-x)FGS" alloys with many intermediate values of x, between 0 and 25 wt.%, 25 and 50wt.%, 50 and 75wt.%, to obtain much more points to more clearly revealing possible effects. Second, one can think applying graphitization and ferritization heat-treatment to the "xFe(1-x)FGS" cast alloys and to the "xCo(1-x)FGS" cast alloys, respectively, to access to the intrinsic contributions of metallic matrix, without any interference or cheating with/ by ledeburite or pearlite. This can be envisaged to better understand the effects of Ni and Co, for an extension of this work.

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