

EFFECT OF NICKEL TYPE ON PROPERTIES OF BINDER-TREATED MIXES

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ABSTRACT

In this paper, the effect of two nickel powders with different size distribution on the physical and mechanical properties of two binder-treated steel powder pre-mixes processed on an industrial scale is discussed. The properties of these two mixes are compared to those of a diffusion-alloyed mix of the same composition. It is shown that the mechanical and dimensional change properties of the binder-treated mixes are superior to those of the diffusion-alloyed mix. It is also shown that the physical and sintered properties of the binder-treated mixes can be further improved by using an extra-fine nickel powder (1.5 μm) instead of a standard size (8 μm) P/M nickel powder.

1. INTRODUCTION

Steel powder grades containing nickel, copper, molybdenum and carbon are of great interest for P/M applications requiring high performance. Indeed, these alloying additives provide P/M steels with good sintered strengths, toughness, hardenability and dimensional change control. Alloying additives can be admixed, diffusion-alloyed or pre-alloyed to steel powders. While pre-alloying leads to homogeneous microstructure and higher mechanical performances, it is generally detrimental to powder compressibility. For this reason, in applications requiring high densities, alloying additives such as copper and nickel are usually admixed to steel powders. Molybdenum, on the other hand, has almost no detrimental effect on the compressibility of iron powders and is usually pre-alloyed to provide maximum hardenability.

The microstructure of steel powders containing admixed alloying additives is homogenized by diffusion. While copper melts, at the typical sintering temperature (1120 $^{\circ}\text{C}$), nickel remains solid and diffusion is incomplete leaving nickel rich areas (NRA's) in the steel microstructure. While these NRA's can be beneficial to toughness and fatigue properties, nickel must be completely diffused in the matrix steel for maximum hardenability and solution hardening effects. There is thus a great interest in finding ways to increase nickel diffusion in P/M steels containing admixed or diffusion-alloyed nickel. Higher sintering

temperatures [1] and/or longer sintering times are efficient in promoting nickel diffusion. However these solutions are not widespread in the P/M industry due to their inherent cost and to the fact that most P/M furnaces are not adapted to high temperature sintering. Recent studies [2] have shown that the use of extra-fine (1.5 μm) nickel powders instead of standard P/M nickel powders (8 μm) could be a good alternative to increase the diffusion of nickel in the steel matrix of typical nickel based P/M steels. In the case of Ni-Cu based P/M steel, it seems that, in addition to improving nickel distribution, the use of extra-fine nickel improves also the distribution of copper by increasing the interaction between nickel and copper during sintering [3].

While attractive, there are several limitations in using very fine powders in P/M steel mixes. Mixing fine powders, for example, can prove difficult. To be able to individually disperse fine powders, intensive mixing or treatments to reduce their inherent cohesiveness are necessary [4]. Indeed, in the micrometer size range, metallic powders tend to agglomerate and are usually cohesive because of the magnitude of inter-particulate forces [5]. Convective mixing, typical of low intensity blenders used in the P/M industry, is too mild to disrupt these agglomerates. The result of the mixing process is a dispersion of these agglomerates in the powder mix and, in turn in the green parts. While fine powders can be potentially beneficial to mechanical properties, when agglomerated they can be detrimental. The other drawbacks of using fine alloying powders in P/M steel mixes are their propensity to generate potentially hazardous dust during handling and pressing, to decrease flowability and to segregate. These problems can however be prevented by binding alloying additives to the surface of the steel powders. Partial diffusion of alloying additives during annealing is the most efficient way to bind them to the surface of steel powders. Organic binders can also be added to the powder mixes to bind the alloying additives to the surface of the iron powders. This latter process yields lower binding strength than partial alloying but is widely used in the P/M industry due to its lower cost.

Binder-treated mixes are of great interest for Ni-Cu based P/M steels. In addition to improving industrial hygiene related to dusting of nickel, segregation of the alloying additives is reduced in such mixes. This usually translates in optimum sintered properties and part-to-part consistency. Using extra-fine nickel in segregation free P/M mixes could thus be an efficient way to optimize the properties of Ni-Cu P/M steels. In this paper, the effect of two nickel powders with different size distribution on the physical and mechanical properties of two binder-treated Ni-Cu-Mo steel powder pre-mixes processed on an industrial scale is discussed. The properties obtained with these two binder-treated mixes are compared with those of a diffusion-alloyed mix of the same composition.

2. EXPERIMENTAL PROCEDURE

Composition and preparation of powder mixes

Two base powders manufactured by Quebec Metal Powders Limited were used in the study: ATOMET 4001, a water atomized pre-alloyed steel powder containing 0.5% Mo and ATOMET DB 46, a diffusion-alloyed powder containing 0.5% Mo, 1.75% Ni and 1.5% Cu.

Two binder-treated steel powder pre-mixes and one regular pre-mix of 68 kg (150 lbs) each were prepared in a twin shell V-Type blender/dryer. The regular mix was prepared by admixing 0.6% natural graphite and 0.75% wax lubricant (Acrawax C, Lonza) to the ATOMET DB 46 powder. This powder mix is identified as AT-DB40A in this study. Two binder-treated pre-mixes, of the same composition as the AT-DB40A mix, were prepared in the twin shell V-Type blender/dryer by using the QMP patented binder technology [6]. The total concentration of lubricant and binder in these two mixes was set to 0.85%. Two different carbonyl nickel powders, INCO T123 PM and INCO T110 D, manufactured by INCO Limited and a fine

commercial copper powder ($D_{50} \sim 15 - 20 \mu\text{m}$) were used in these mixes. The binder-treated mix containing the INCO T123 PM and T110 D nickel powders are identified in this study respectively as F40A-123 and F40A-T110. The particle size distribution of these two nickel powders, as measured by laser diffraction particle size analysis is given in Table 1. The characteristics of the steel mixes used in that study are summarized in Table 2.

Table 1. Particle size distribution (Volume %) of the two nickel powders used in the study

Nickel Type	D_{10} (μm)	D_{50} (μm)	D_{90} (μm)
INCO 123	1.25	8	20
INCO T110	0.5	1.5	4.7

Table 2. Characteristic of the mixes used in that study

Mix Identification	Size (kg)	Type of mix	Pre-alloyed additives wt%		Diffusion additives wt%		Admixed additives wt%		
			Mo	Mn	Ni	Cu	Ni	Cu	C
AT-DB40A	68	Regular/Diffusion alloyed	0.5	0.15	1.75	1.5			0.6
F40A-123	68	Binder-treated	0.5	0.15			1.75 (T123 PM)	1.5	0.6
F40A-T110	68	Binder-treated	0.5	0.15			1.75 (T110 D)	1.5	0.6

Powder and green characterization

The following properties: apparent density, flow rate, green strength, compressibility, nickel distribution and dust resistance factors were measured for the powder mixes AT-DB40A, F40A-123 and F40A-T110. The apparent densities and flow rates of the powder mixes were determined according to MPIF Standards 03 and 04. The green transverse rupture strengths of the powder mixes were determined according to MPIF Standard 41 on a set of five test specimens pressed at 25 °C to a density of 7.0 g/cm³ in a double action floating-die. Compressibility curves at 25 °C were drawn for all the powder mixes according to MPIF Standard 45. The graphite, copper and nickel dusting resistances were determined by an elutriation method. The powder mixes were placed in a 2.5 cm diameter steel tube and fluidized with air at a constant flow rate of 6.0 liters/minute for five minutes. This causes the dust to be entrained as a result of a large surface-to-volume ratio and, in the case of graphite, low specific gravity. The mixture remaining on the screen plate was then analyzed to determine the relative amount of carbon copper and nickel. The dusting resistance factors for carbon, copper and nickel were expressed as a percentage of the initial mix concentrations.

Sintered and tensile properties

Sets of 5 transverse rupture test specimens of the powder mixes AT-DB40A, F40A-123 and F40A-T110 were pressed at room temperature and compacting pressures of 550 MPa (40 tsi), 690 MPa (50 tsi) and 760 MPa (55 tsi). Green densities were 7.04, 7.15 and 7.19 g/cm³ for the powder mixes F40A-123 and F40A-T110 and 7.04, 7.17 and 7.21 for powder mix AT-DB40A. All of the transverse rupture test

specimens were pressed in a double action floating-die and were sintered for 30 minutes at 1120 °C (2050 °F) in a nitrogen base atmosphere, containing 5% hydrogen, in a commercial mesh-belt furnace. The cooling rate in the range 650-400 °C was about 0.6 to 1.5 °C/sec. All the sintered transverse rupture test specimens were tempered at 205°C for an hour in air before mechanical testing. An additional set of 5 transverse rupture test specimens pressed at 550 MPa was also tested as sintered. Transverse sintered strength, apparent hardness and dimensional change of all the specimens were evaluated according to MPIF Standard 41, 43 and 44 respectively.

Tensile test specimens, of the powder mixes AT-DB40A, F40A-123 and F40A-T110, were pressed to densities of 7.0 and 7.2 g/cm³. These specimens were pressed on an industrial 150 ton mechanical press at a stroke rate of 10 parts per minute. Limited runs of 250 tensile specimens (89.64 X 5.72 X 6.35 mm) were carried out for each powder and density. Standard filling parameters were used to fill the die. The tooling was not heated so that the temperature of the die was at room temperature at the beginning of the runs but increased to reach a plateau after few parts. For each powder mix, the run started when the die temperature reached the steady state. For each run, forty samples were selected at random for sintering and testing. All of the samples were sintered in the same conditions as the transverse rupture test specimens. Half of the sintered tensile specimens were tempered at 205 °C for an hour in air before mechanical testing. Tensile properties were determined according to MPIF Standard 10. Apparent hardness (HRA) was measured, in the as sintered state and tempered state, on the side faces of the specimens.

Microstructural evaluation

Tensile specimens of the powder mixes DB40A, F40A-123 and F40A-T110 were selected at random, cut, mounted and polished for microstructural evaluation. Microstructures were evaluated after etching with a solution 2% nital- 4% picral. Microindentation hardness (HV 10 gf) was also measured. Finally, in order to evaluate the repartition of the different alloying elements in the steel microstructures of the different powder mixes, energy dispersive spectrometry (EDS) mappings at 250 X of iron, copper and nickel were carried in a scanning electron microscope (SEM).

3. RESULTS AND DISCUSSION

Powder and green characterization

The flow rate, apparent density, green strength and compressibility of the powder mixes DB40A, F40A-123 and F40A-T110 are reported in Table 3 and Figure 2.

Table 3. Flow and green properties

Mixture Identification	Apparent density, g/cm ³	Flow rate, sec./50 g	Green strength (7 g/cm ³)	
			MPa	psi
AT DB40A	3.19	35	8.7	1270
F40A-123	3.19	27	9.4	1360
F40A-T110	3.14	27	9.8	1420

The flow rates of the two binder-treated mixes are similar but faster than that of the regular diffusion-alloyed mix. The slow flow rate of the regular diffusion-alloyed mix is typical and has been associated to strong adhesion forces introduced by wax type lubricants [7]. Binding the wax lubricant reduces the stickiness of the powder mix resulting in an improved flow behaviour. The binder-treated mixes and the

regular mix exhibit similar low green strength. This is also typical of green compact containing wax type lubricants and is associated with the lack of metal-to-metal contact due to smearing of these lubricants during mixing. Partial alloying seems to affect powder compressibility of the diffusion-alloyed mix at compacting pressures below 550 MPa (40 tsi). At pressures higher than 690 MPa (50 tsi) the tendency was reversed with the diffusion-alloyed mix having a higher compressibility than the binder-treated mixes. This is related to the slightly lower concentration of organics in the diffusion-alloyed mix.

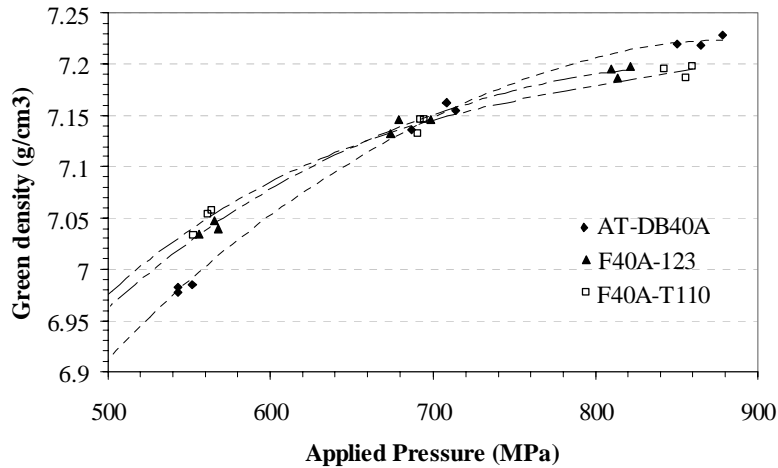


Figure 2. Compressibility of powder mixes DB40A, F40A-123 and F40A-T110.

The biggest difference in powder properties between the powder mixes is their dust resistance factors for nickel and copper. Figure 3 shows the dust resistance factor for graphite, copper and nickel of the powder mixes DB40A, F40A-123 and F40A-T110.

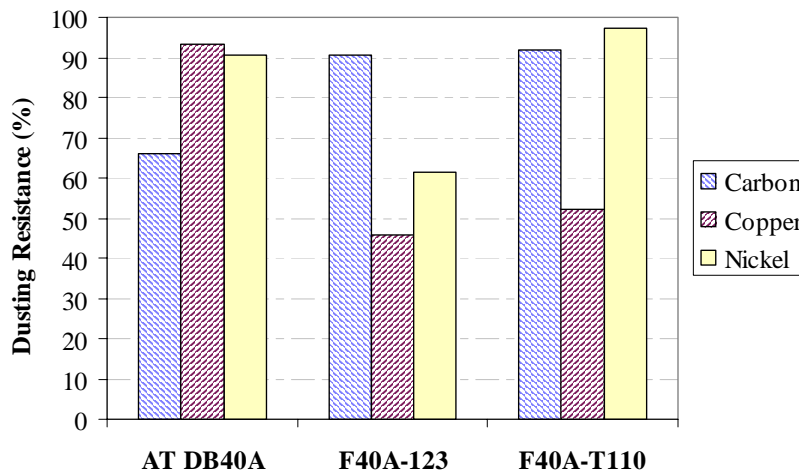


Figure 3. Compressibility of powder mixes AT-DB40A, F40A-123 and F40A-T110. Note that 100% means no dusting loss while 0% means total loss of additive.

Dusting resistance for copper and nickel in the diffusion-alloyed mix is virtually 100%. The fact that a somewhat lower value has been recorded is related to the fact that the air stream can entrain fine iron powders containing nickel and copper. The mean dust resistance for graphite is around 90% for the binder-treated mixes but could be readily increased above 95% by selecting appropriate binding parameters. Dusting resistance for copper is between 45 to 50% for the two binder-treated mixes, which is typical of

binder-treated mixes containing commercial copper powders. It should be noted that the dusting resistance of copper in regular non-bonded mixes is of the order of 20 to 25%. The dusting resistance for graphite, while admixed, in the diffusion-alloyed mix is higher than that of copper, 60% versus ~50%. Fine natural graphite powders have large flat surfaces giving them the ability to adhere to bigger powders by adhesive (van der Waals type) forces.

Almost no nickel dusting loss was recorded for the binder-treated mix containing the extra-fine INCO T110 D powder. Nickel dusting resistance was around 60% for the binder-treated mix containing the standard INCO T123 PM powder compared to ~25% in regular mixes. Reduced dusting tendency of extra-fine nickel powder has been measured in previous study and has been confirmed independently in recent studies by other iron powder manufacturers [8,9]. However, contrary to the study by Nichols and Sawayama, in this study the extra-fine nickel powder was not only more efficiently bonded, but also more uniformly dispersed in the powder mix. These different findings may be related to the different binders, base powder and/or processing methods used to prepare the binder-treated mixes. While finer, the use of extra-fine nickel in binder-treated mixes could be an efficient way to improve the industrial hygiene related to nickel dusting at a reduced cost compared to diffusion-alloyed mixes for an equivalent efficiency. Figure 4 shows SEM micrographs of typical bonded iron powders in the binder-treated and diffusion-alloyed powder mixes. Iron powders in the binder-treated mix containing the extra-fine nickel are clearly more uniformly covered with nickel than iron powders in the binder-treated mix containing the standard nickel powder.

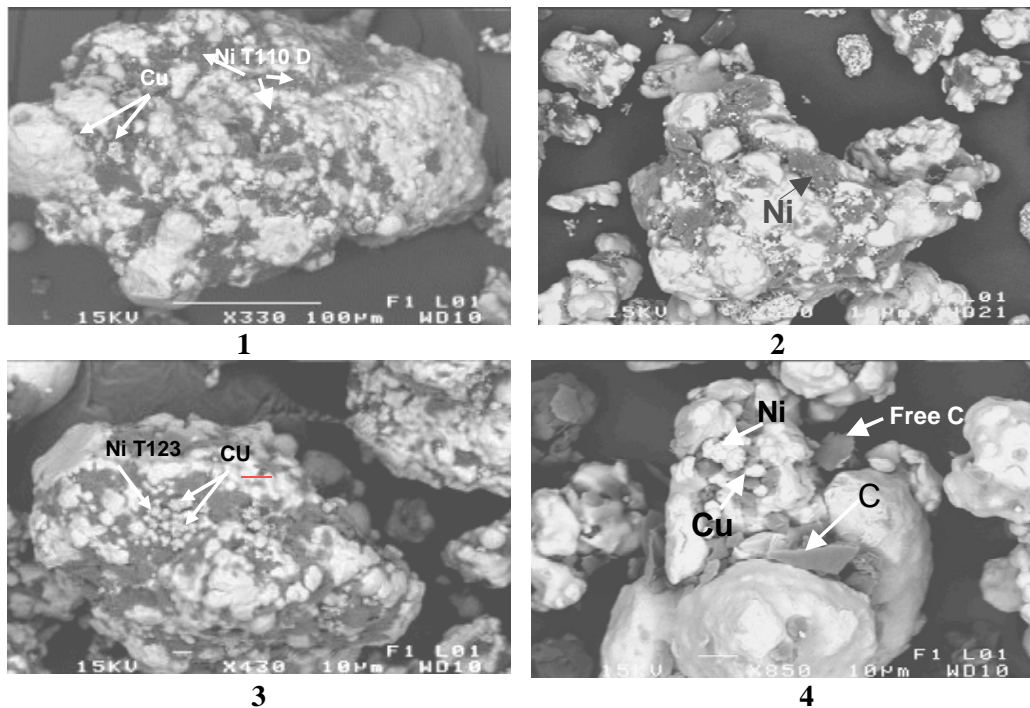


Figure 4. Backscattered S.E.M images showing the aspect of iron powders in the powder mixes F40A-T110 (1 and 2), F40A-123 (3) and DB40A (4). Binder is located mainly in the black areas that contain also graphite, lubricant, copper and nickel.

Sintered and tensile properties

Results of the transverse rupture tests are summarized in Figures 5 to 10. Otherwise indicated, all the results refer to specimens in the as-sintered and as-tempered state. Figure 5 shows that the dimensional change (DC) from die size was positive for all the powder mixes while DC from green size was negative.

Shrinkage actually happened during sintering, the final positive dimensional changes were due to spring-back after ejection of the parts. Dimensional changes for the binder-treated mixes were more negative than for the diffusion-alloyed mix at all compacting pressures. The binder-treated mix containing the extra-fine nickel powder exhibited more negative dimensional change than the binder-treated mix containing the standard nickel powder. Figure 6 shows that the difference of dimensional change between the binder-treated mix F40A-T110 and the other two powder mixes is more pronounced as compacting pressure increases. It is interesting to note that the difference in DC between the binder-treated mix containing the extra-fine nickel powder and the other two powder mixes varies linearly with the compacting pressure with an equal slope. The more negative DC yielded by the binder-treated mix F40A-T110 compared to the binder-treated mix F40A-123 is associated with more nickel diffusion in the iron matrix. As density increases, this shrinkage effect also increases. The more positive DC recorded with the diffusion-alloyed mix might be due to slight differences in the copper powder size and/or distribution or to the partial diffusion of nickel and copper in the iron matrix that occurred during the annealing of the iron/copper/nickel mixture. The results seem to indicate that at lower density ($< 7.0 \text{ g/cm}^3$), copper controls the dimensional changes. Indeed DC is similar for the two binder-treated mixes. At higher compaction pressures, copper still has an effect but the effect of nickel on DC becomes more important.

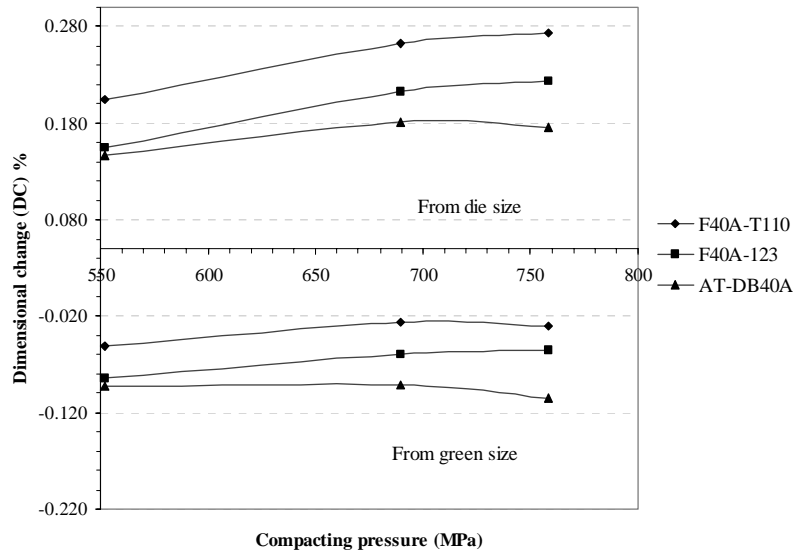


Figure 5. Mean dimensional change as a function of the applied pressure.

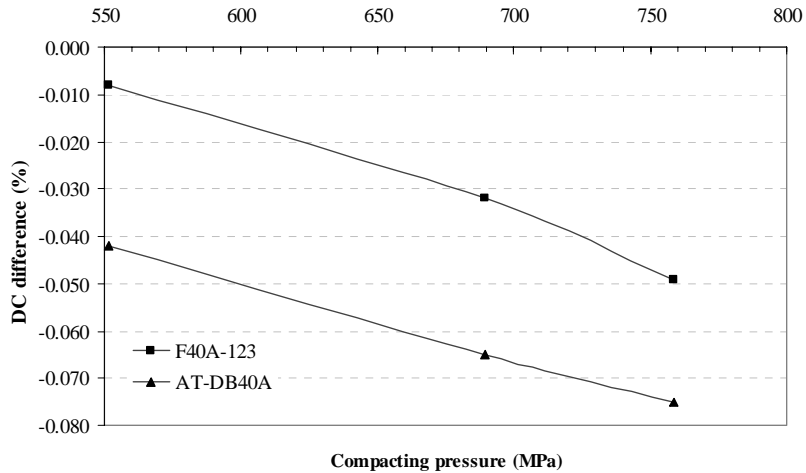


Figure 6. DC difference between the powder mix F40A-T110 and the two powder mixes: F40A-123 and AT-DB40A.

Evidence of more nickel diffusion in the binder-treated mix containing the extra-fine nickel powder can be seen in Figure 7, where the density variation after sintering of the specimens is reported. The density loss was less for the binder-treated mix containing the extra-fine nickel powder, as a result of the swelling effect of Cu being counter-acted by the increased shrinkage of the extra-fine Ni powder. Figure 8 shows that dimensional change is affected by tempering. The DC was more negative after tempering for all the powder mixes. This result has already been observed in other studies and was related to the proportion of martensite and level of carbon in the specimens [10]. The fact that more variation in DC after tempering was recorded for the binder-treated mix containing the extra-fine nickel powder indicates that the proportion of martensite is higher in the specimens of this mix.

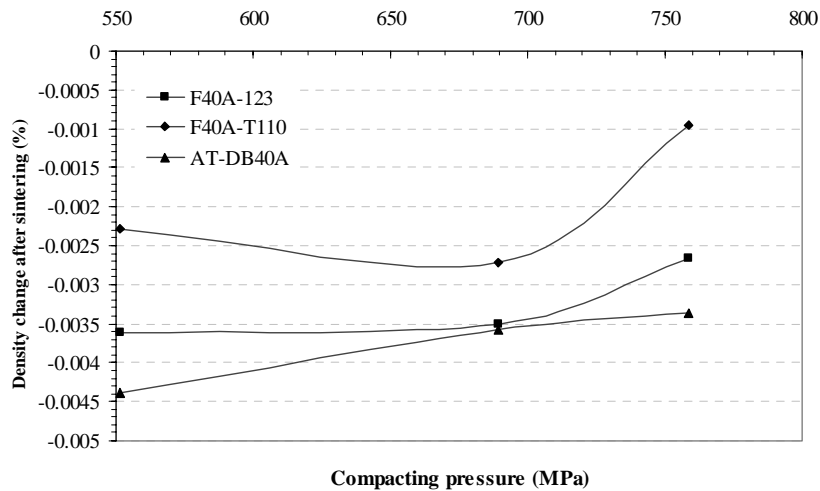


Figure 7. Density variation after sintering as a function of the applied pressure.

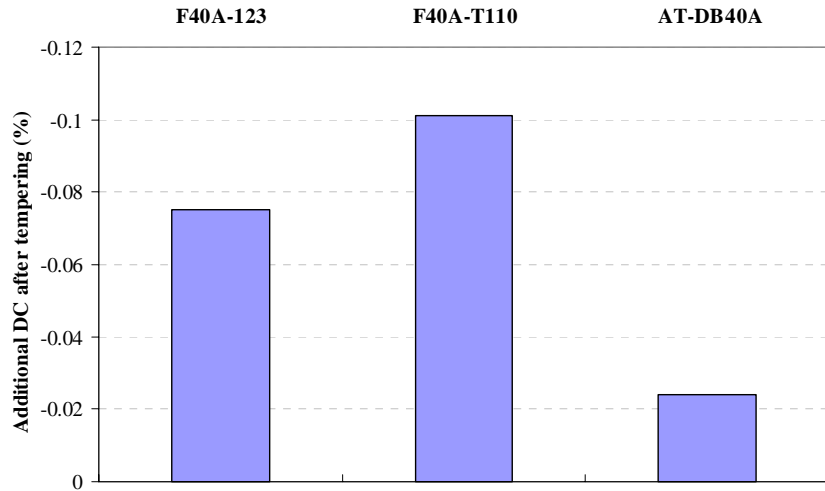


Figure 8. Variation of DC for specimens pressed to 7.0 g/cm^3 , sintered and tempered at 205°C for 1 hour in air.

Results of the sintered transverse rupture strength tests are reported in Figure 9. The TRS strengths of the binder-treated mixes were found to be higher than those of the diffusion-alloyed mixes, especially at low density. The TRS for the binder-treated mix containing the extra-fine nickel was found to be slightly higher (4%) than for the binder-treated mix containing the standard nickel and 5 to 10% higher than the diffusion-alloyed mix. Careful examination of Figures 7 and 9 indicates that sintered strength followed the same trend as the density change of the specimens after sintering.

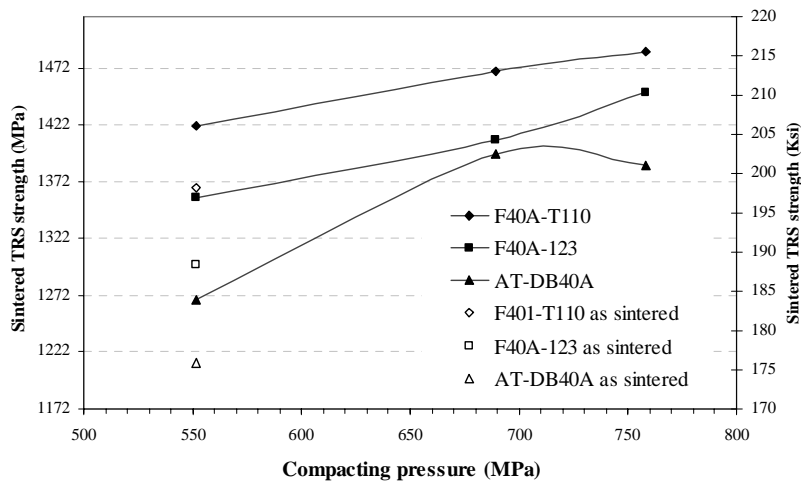


Figure 9. TRS strength as a function of the compacting pressure.

The tempered apparent hardness results are reported in figure 10. The trend is once again the same: the apparent hardness of the binder-treated mix containing the extra-fine nickel powder is superior to those of the other two mixes.

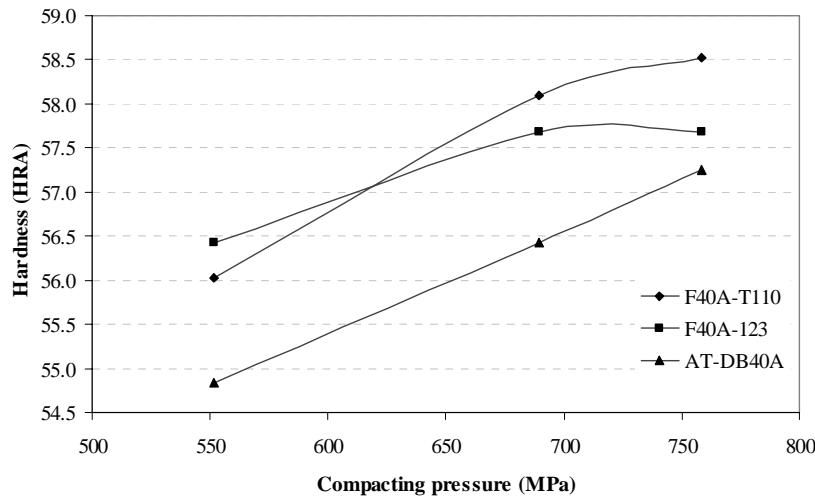


Figure 10. Apparent hardness as a function of the compacting pressure.

The results of the tensile tests are reported in Tables 4 and 5. As for the TRS tests, the tensile properties of the binder-treated mixes were found to be higher than those of the diffusion-alloyed mix. For specimens pressed to 7.0 g/cm^3 , the as-sintered UTS and yield stress of the binder-treated mix containing the extra-fine nickel powder were found to be 5% higher than those of the binder-treated mix containing the standard nickel powder and 20% higher than those of the diffusion-alloyed mix. At 7.2 g/cm^3 , the difference in as sintered UTS and yield stress of the F40A-T110 mix with the F40A-123 mix grew to 8 to 10% while this difference fell to 13 to 15% with the diffusion-alloyed mix.

Table 4. As-sintered tensile properties. Average of 20 samples.

Mix ID	Green density (g/cm^3)	UTS (MPa)		Yield at 0.2% of plastic strain (MPa)		Maximum elongation (%)		Apparent Hardness (HRA)
		Average	Standard deviation	Average	Standard deviation	Average	Standard deviation	Average
DB40A	7.00	560	28	420	13	1.8	0.13	50.5
	7.20	650	9	485	4	1.8	0.12	54.8
F40A-123	7.00	660	16	490	9.6	1.7	0.13	50.3
	7.20	690	41	520	13	1.6	0.32	55.8
F40A-T110	7.00	690	23	510	8.7	1.7	0.11	54.5
	7.20	740	13	545	6.7	1.7	0.12	56.3

Tempering increased the yield stress of the specimens of all three powder-mixes at all the densities evaluated. This effect was usually more pronounced for the binder-treated mix containing the extra-fine nickel (7% increase vs 4.5% for the other mixes) except for specimens pressed to 7.0 g/cm^3 where an increase of 9% was recorded for the diffusion-alloyed mix. The elongation remained almost unchanged for all the materials, which is typical for such a formulation with $\sim 0.50\%$ sintered carbon. UTS was also increased by the tempering treatment for the binder-treated mix containing the extra-fine nickel powder at all densities. This gain was however more modest than for the yield stress (4% vs 7%). The effect of tempering on UTS for the other mixes was minimal. Apparent hardness was also basically unchanged by

tempering for all three mixes. Similar findings have been reported in other studies of similar materials [11]. It has been reported that tempering releases residual stresses that affect principally the yield stress. The fact that tempering affected more positively and more consistently the tensile properties of the binder-treated mix containing the extra-fine nickel powder is an indication of a more uniform microstructure containing more martensite phases. DC changes after tempering of TRS specimens presented before also support this claim.

Table 5. Sintered tensile properties after tempering. Average of 20 samples.

Mix ID	Green density (g/cm ³)	UTS (MPa)		Yield at 0.2% of plastic strain (MPa)		Maximum elongation (%)		Apparent Hardness (HRA)
		Average	Standard deviation	Average	Standard deviation	Average	Standard deviation	
DB40A	7.00	589	20	462	9	1.9	0.11	50
	7.20	643	25	505	8	1.8	0.13	54.4
F40A-123	7.00	665	26	511	10	1.8	0.19	51.5
	7.20	711	22	544	9	1.9	0.31	55.5
F40A-T 110	7.00	723	10	551	6.3	1.9	0.17	53.7
	7.20	770	19	586	10	1.9	0.19	55.5

Microstructural evaluation

The phases constituting the microstructure of the three powder mixes under study were similar. A typical microstructure is shown in Figure 11 where areas of fine pearlite (300 HV 10 gf), divorced pearlite (180 HV 10 gf), martensite (500 to 740 HV 10 gf) and retained austenite (150 to 200 HV 10 gf) can be seen. The proportion of the different phases was not evaluated and might have been different from one powder formulation to another.

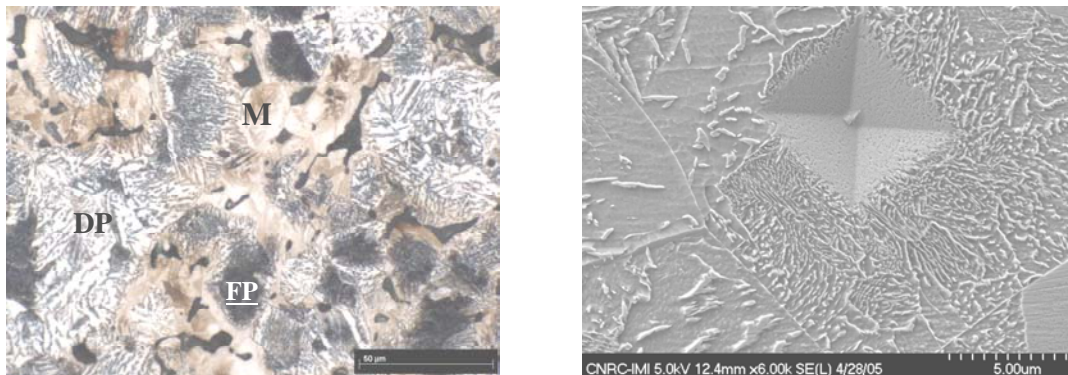


Figure 11. Typical microstructure showing fine pearlite (black phase) bordered by divorced pearlite, martensite (brownish areas) and nickel-rich retained austenite (white areas). At the right, high magnification of a typical black phase showing fine pearlite. Mix F40A-123 pressed to 7.0 g/cm³.

EDS mapping experiments revealed obvious differences in the distribution of the nickel rich areas (NRAs) in the microstructure of specimens of the three powder-mixes (Figs. 12-14). Note that the A picture in each

Figure is the back-scattered electron (BSE) image of the elemental mapping field. Figures 12 and 13 clearly show that NRA's are more evenly distributed in the microstructure of the binder-treated mix containing the extra-fine nickel powder. Highly concentrated NRA's could be observed in the microstructure of the binder-treated mix containing the standard nickel powder. In the binder-treated mix containing the extra-fine nickel powder NRA's were usually better distributed and smaller in size, indicating more nickel going into solution in the iron matrix. The concentrated nickel areas in the specimen of the binder-treated mix containing the standard nickel powder were also found to be associated with concentrated copper areas. As a result copper distribution was less uniform in the specimen of this mix. It is interesting to note that the NRA's located around large pores contain high level of copper while highly concentrated NRA's located in dense areas contain almost no copper. This result associated with the fact that when copper melts, it always leaves pores behind corresponding to its size. The higher mechanical properties and the reduced swelling of the binder-treated mix containing the extra-fine nickel powder are believed to be mainly associated with: i) the more uniform dispersion of NRA's and copper and ii) more solution hardening due to increased amount of nickel diffused in the iron matrix.

NRA's in the diffusion-alloyed mix were also found to be more concentrated in nickel than NRA's of the binder-treated mix containing the extra-fine nickel powder. However, contrary to the binder-treated mix F40A-123, copper agglomeration was not obvious in concentrated NRA's. Copper distribution was virtually not affected by nickel distribution in the diffusion-alloyed mix. This result might be an indication that partial alloying of copper occurred during the annealing process of the iron/nickel/copper mixture. This phenomenon and the fact that less nickel seems to go into solution in the iron matrix might explain the more positive DC and the lower mechanical properties recorded with the diffusion-alloyed mix.

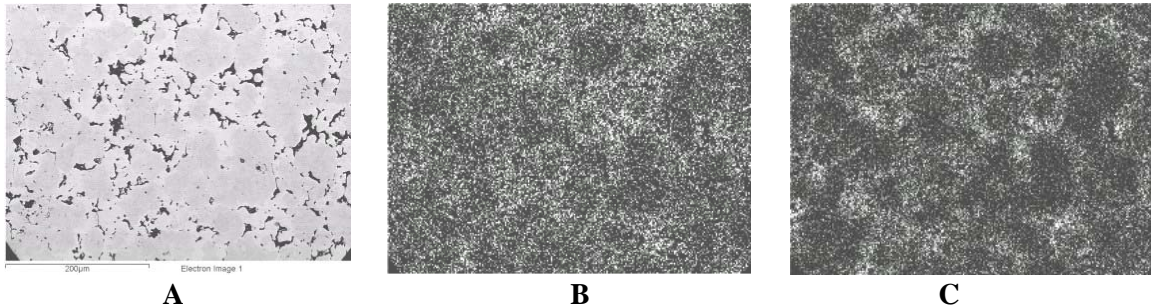


Figure 12. Mapping showing dispersion of copper (B) and nickel (C) in the powder mix F40A-T110 after compaction to 7.2 g/cm^3 and sintering at 1120°C for 30 minutes.

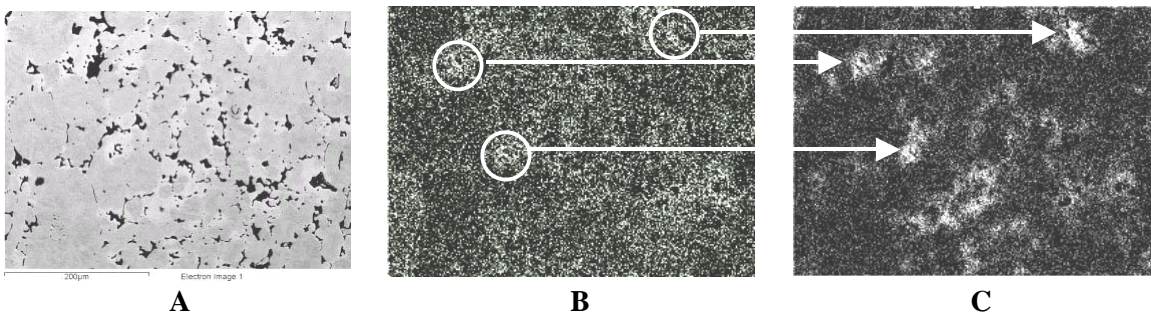


Figure 13. Mapping showing dispersion of copper (B) and nickel (C) in the powder mix F40A-123 after compaction to 7.2 g/cm^3 and sintering at 1120°C for 30 minutes. Agglomerates of copper and nickel associated near porosity. In dense areas agglomerated nickel does not associate with copper.

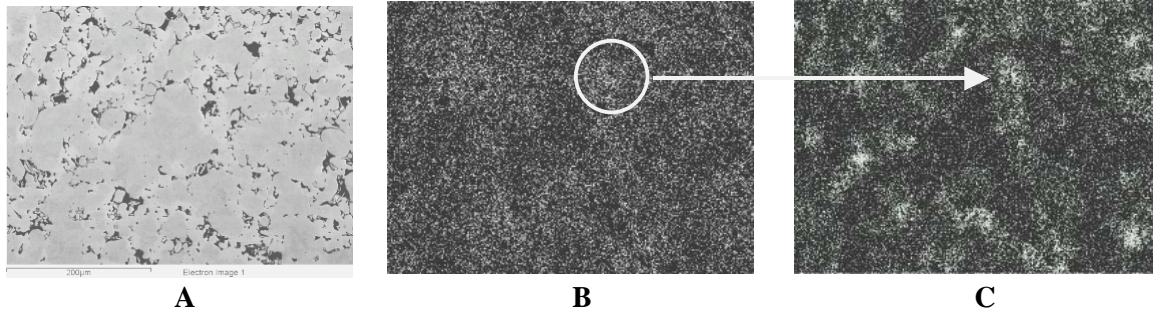


Figure 14. Mapping showing dispersion of copper (B) and nickel (C) in the powder mix AT-DB40A after compaction to 7.2g/cm^3 and sintering at 1120°C for 30 minutes. Note that agglomeration of nickel does not result in agglomeration of copper as for the mix F40A-123.

4. CONCLUSIONS

The effect of two nickel powders with different size distribution on the physical and mechanical properties of two binder-treated Ni-Cu-Mo steel powder pre-mixes was presented. The properties obtained with these two binder-treated mixes were further compared to those of a diffusion-alloyed mix of the same composition.

The results showed that:

- i) The use of extra-fine nickel powders reduces significantly nickel dusting in binder-treated mixes, to levels as low as nickel dusting levels of diffusion-alloyed mixes.
- ii) TRS and tensile properties of the two binder-treated mixes under study were superior to those of their diffusion-alloyed counterpart. The binder-treated mix containing the extra-fine Ni powder showed the largest improvements. TRS were 5 to 10% higher than those of the diffusion-alloyed mix while UTS and yield stress were 15 to 20% higher.
- iii) Increased densification was measured for the binder-treated mix containing the extra-fine Ni powder. As density increases this shrinkage effect also increases. As a result of the increased shrinkage, the density after sintering of the binder-treated mix containing the extra-fine Ni powder was higher than for the diffusion-alloyed mix and the binder-treated mix containing the standard Ni powder.
- iv) NRA's are more evenly distributed and less concentrated in nickel in the microstructure of the binder-treated mix containing the extra-fine nickel powder. As a result, Cu distribution is improved in the microstructure of the binder-treated mix containing the extra-fine nickel powder.

This study clearly showed that the properties of binder-treated mixes can be improved over those of equivalent diffusion-alloyed mixes. The use of extra-fine Ni powders instead of standard P/M nickel powders can further extend these improvements. In binder-treated mixes containing nickel, copper, carbon and molybdenum as alloying elements, these improvements are associated with i) the more uniform dispersion of NRA's and as a consequence of copper in the steel microstructure and ii) more solution hardening due to increased nickel diffusion. The results suggest that the beneficial impact of the XF Ni powder increases with density. The effect of using extra-fine Ni powders on the properties of P/M parts pressed to high densities should be investigated.

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