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DEVELOPMENT OF HIGH COMPRESSIBLE LEANER ALLOYED STEEL POWDERS EQUIVALENT TO MO-NI-CU DIFFUSION-BONDED POWDERS

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ABSTRACT

Diffusion-alloyed powders such as FD-0405 (0.5Mo-4Ni-1.5Cu) and FD-0205 (0.5Mo-1.75Ni-1.5Cu) are widely used in the industry for the production of high performance parts. However, the rising price of alloying elements such as Mo, Ni and Cu between 2004 and 2008, coupled with the potential regulation issue with Ni and the constant requirement to produce high performance parts at the lowest possible cost, have led to the introduction of cost effective alloyed powder alternatives including powders with Cr, Mn and Si, pre-alloyed or added as ferro-alloys. Nevertheless, these types of alloys are not so easy to process, requiring higher sintering temperature and very well controlled sintering conditions with very low dew point. Their compressibility is also not so good.

Another approach is to develop optimized alloys based on pre-alloyed Mo powders combined with lower levels of Cu and Ni. Such alloys show excellent compressibility and remain easy to sinter under normal sintering conditions with various atmospheres. In addition, efficient bonding technique such as diffusion-bonded and binder-treatment processes allow achieving excellent Ni bonding. The results of studies carried out over the last years and aiming for the development of such optimized leaner powders using cost effective processing technologies are presented.

INTRODUCTION

Mo, Ni and Cu elements are widely utilized in combination in PM materials because they allow achieving unique microstructure, which in turn leads to very good static and dynamic properties [1,2,3]. For such alloyed systems, Mo is preferably pre-alloyed to the iron due to its beneficial effect on hardenability and its very limited drawback on compressibility while elemental Ni and Cu powders are admixed, diffusion-alloyed or bonded by a chemical process called binder-treatment to the Mo base powder. Addition of Ni and Cu powder can be easily done with other additives such as graphite and lubricant to the steel powder during the mixing operation. However, the Ni and Cu bonding achieved is poor, which may result in greater segregation during powder handling and pressing and more heterogeneity in the parts. Also, high level of Ni dusting around the press during compaction can be obtained as demonstrated by Thomas et al [4]. A second route consists in diffusion-bonding the Cu and Ni to the base steel powder during a second annealing step. Excellent bonding is achieved with this process, which is believed to help maintain higher level of homogeneity within the part and from part-to-part. The excellent bonding also results in very limited dusting in the work area [4]. This process is however more expensive due to the second annealing step and deteriorates to a certain level the compressibility, even if annealing conditions are optimized to maximize the Ni and Cu bonding while maintaining compressibility as high as possible. The third route consists in the binder treatment of the mix. Generally all additives including the elemental Ni and Cu as well as graphite, lubricant and other additives are admixed prior to the binder treatment [5]. This technique provides better Ni and Cu bonding than the conventional admixing route but not like the diffusion-alloyed one. Better Ni and Cu bonding can be achieved when binder-treating the steel powder admixed with Ni and Cu only. The other additives are then conventionally admixed after the binder-treatment. Bonding strength is such that subsequent admixing after binder-treatment has only a minute effect on Ni and Cu bonding. The characteristics of binder-treated powders equivalent to the FD0205 and FD0405 formulations can be found in ref. 6, 7, 8. The bonding strength of Ni and Cu as achieved with the different processing methods is illustrated in Figure 1 [9].

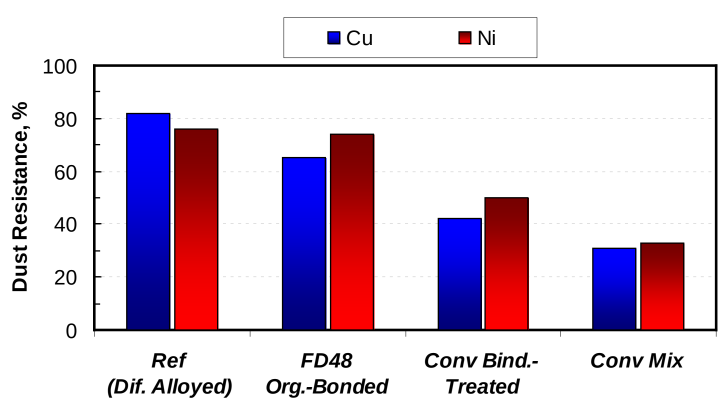


Figure 1. Ni and Cu dust resistance of various type of 4Ni-1.5Cu-0.5Mo steel powders.[6]

The cost aspect is of course a very important factor when selecting a powder system for a given applications and even if the price of Mo and Ni has significantly dropped since their peak values in 2008, their price today remains significantly higher relative to the iron, 33 and 60 times higher for Ni and Mo, respectively [10]. The cost was therefore a key driver for the development of new cost effective alloyed powders during the last 10-15 years. Alloys containing Cr, Mn and Si for instance were developed and introduced to the market [11,12,13]. Such alloys provide very interesting properties but are in general more difficult to process, requiring higher sintering temperature and/or the use of very low dew point atmosphere, eliminating basically sintering under Endo gas atmosphere.

Other considerations also play a role in the development of new alloys such as the consideration of health effects. In particular, in the case of Ni, the processing in powder forminvolves health concerns [14]. Other concerns are product availability and scrap recycling. For all these reasons, development of Ni-free powders or powders with lower Ni contents is still of interest. However, reducing and/or eliminating Ni is not an easy task, since this element brings several advantages related to the mechanical properties.

Several studies were initiated since 2008 with the aim to acquire a better understanding of the effect of alloying elements and carbon on the mechanical properties as well as cost and to develop leaner Mo-Ni-Cu powders equivalent to diffusion-bonded powders such as FD-0405 (0.5Mo-4Ni-1.5Cu) and FD-0205 (0.5Mo-1.75Ni-1.5Cu). The results of such studies were presented in references 15, 16. However, two different approaches were used in these studies. The organic-bonded technology, which consist in preferentially binder-treating the Ni and Cu, was used to develop leaner powder mixes compared to the FD-0405 system while the use of an experimental master diffusion-bonded powders diluted with Mo steel powders to achieve the desired chemistry was investigated in another study. The main results and outcome of these studies are reviewed in this paper. In particular, new results obtained under fast cooling conditions are presented and discussed. Properties of lean alloys developed with the expert program within the scope of these projects and meeting some criteria are also presented.

DEVELOPMENT OF LEAN FD0405 POWDERS

1. Experimental Procedures

Design of experiments (DOE) Taguchi L9 was used in this study to first evaluate the effect of 4 factors: Ni addition (2.5, 3 and 3.5%), graphite addition (0.5, 0.6 and 0.7%), level of pre-alloyed Mo (0, 0.5 and 0.85%) and Cu addition (1, 1.25 and 1.5%). Table 1 gives the exact formulation of prepared mixes. A fine Cu identical to the one used in the reference powder was used. An extra-fine Ni was also used. 0.6% Acrawax C atomized was also added in each mix. Since binder-treatment has no direct influence on sintered properties, mixes were prepared by conventional admixing method. A reference mix corresponding to the MPIF standard 35 FD-0405 mix was also prepared with the diffusion-alloyed grade ATOMET DB48 (0.5%Mo, 4%Ni and 1.5%Cu). The levels of Ni and Cu were intentionally kept lower compared to the reference material in order to maintain the overall cost lower. A high purity graphite grade called CarbQ was used for all the mixes. Steel powders ATOMET 1001, 4001 and 4401 produced by Rio Tinto Metal Powders were used for the 0, 0.5 and 0.85% Mo levels, respectively. A relative cost index was also calculated for each mix with a method described in ref. 15 and the most recent data available on price for alloys (Q4 2013). The cost index for the reference was equal to 1. The cost index for all mixes varied from 0.58 to 1.0 with an average of 0.83. Note that this value remained quite stable since 2008 despite significant change in alloys price.

Sintered properties were evaluated by means of standard TRS and tensile dog bone specimens pressed to a density of 7.0 g/cm³ at room temperature and sintered in two different conditions:
A- standard conditions in a laboratory furnace at 1130°C for 25 min in a nitrogen- 10% hydrogen

atmosphere, B- fast cooling conditions in a production furnace at 1120°C for 20 minutes in a nitrogen- 10% hydrogen atmosphere. The cooling rate from 650 to 400°C was ~0.8°C/sec and ~1.3 °C/sec respectively. Half of specimens were subjected to a tempering carried out at 200°C for 1 hr in air. However, in this section only results after tempering are presented.

Table 1. Description of prepared mixes (Taguchi L9). All mixes contain 0.6% EBS wax.

Mix #	Pre-alloyed Mo, %	Admixed Ni, %	Admixed Cu, %	Graphite, %	Cost index
1	0.0 (1001)	2.5	1.0	0.5	0.67
2	0.5 (4001)	2.5	1.25	0.6	0.77
3	0.85 (4401)	2.5	1.5	0.7	0.84
4	0.5 (4001)	3.0	1.5	0.5	0.85
5	0.85 (4401)	3.0	1.0	0.6	0.88
6	0.0 (1001)	3.0	1.25	0.7	0.76
7	0.85 (4401)	3.5	1.25	0.5	0.96
8	0.0 (1001)	3.5	1.5	0.6	0.84
9	0.5 (4001)	3.5	1.0	0.7	0.89
AVG	*0.5*	*3.0*	*1.25*	*0.6*	0.83
REF	1.25	4.0	1.5	0.6	1.00

2. Effect of Mix Formulation on Properties

One clear benefit of admixing Ni and Cu instead of diffusion-alloying them is compressibility. As illustrated in Figure 2 showing the compressibility curves for mixes grouped by their level of Mo versus the diffusion-alloyed reference, all mixes showed better compressibility than the reference. Typically, the difference in pressure at 7.0 g/cm³ was around 40 MPa (3 tsi). The gain in density obtained when pressing at equivalent compacting pressure varies from 0.04 to 0.06 g/cm³ at around 500 MPa (36 tsi). It is also worth noting in Fig. 2 that increasing the Mo content in base powder had almost no effect on compressibility, which is one of the advantages of using Mo to increase hardenability of the base powder. It should be noted that using binder-treatment to bond Ni and Cu will have minute effects on compressibility.

The effect of each factor on the apparent hardness, dimensional change, tensile strength (UTS) and elongation is illustrated in Figure 3. It is important to take note that the X axis is not linearly

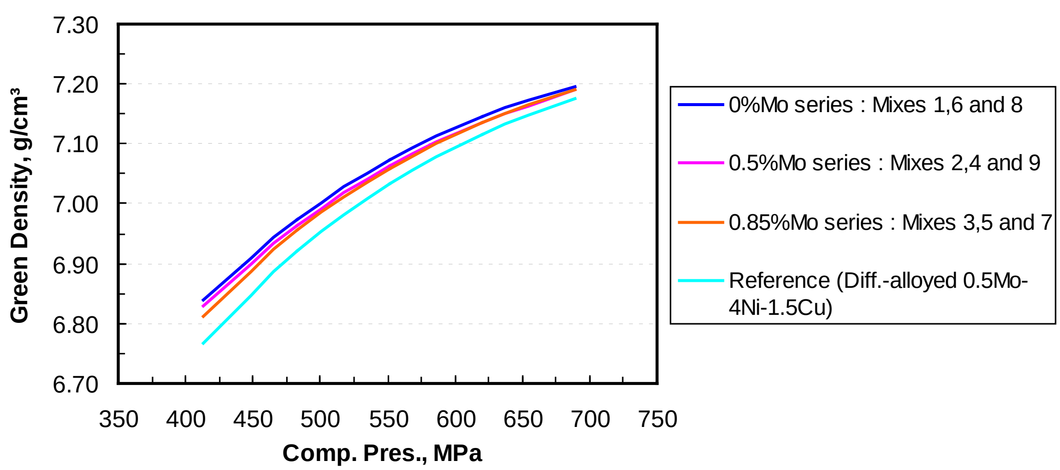


Figure 2. Compressibility curves for mixes regrouped by level of pre-alloyed Mo.

scaled but the figures allow to easily evaluate which factor has the highest influence on each property. Also, the red dotted line represents the average value achieved for the 9 mixes tested while the green dotted line represents the value obtained with the reference mix. It is interesting to note that for all the properties, the average values for the nine mixes were very similar to the values achieved with the reference mix.

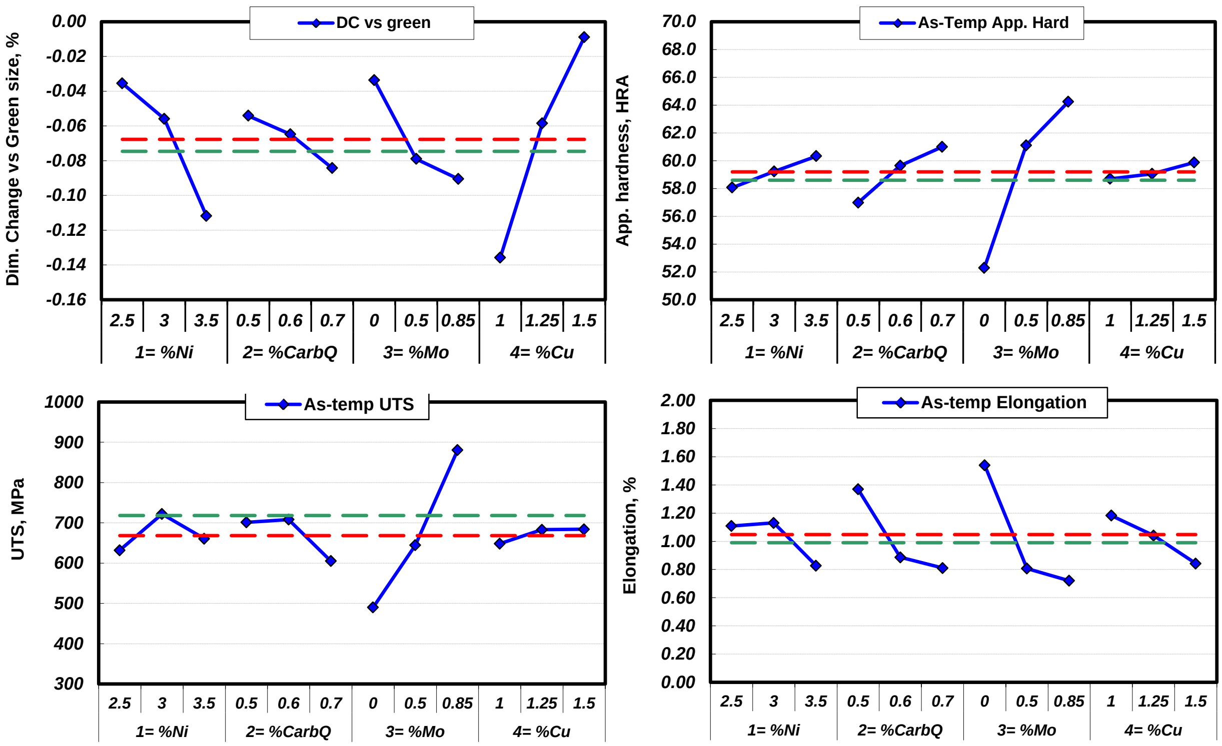


Figure 3. Effect of Ni, graphite, pre-alloyed Mo and Cu content on as-tempered properties at 7.0 g/cm³. Specimens were sintered at 1120°C for 20 min and fast-cooled (1.3°C/sec).

Increasing Ni, graphite and Mo content led to more negative dimensional change while increasing Cu content had the opposite effect. Cu content had the strongest effect on dimensional change, followed by Ni and Mo. The effect of Cu on dimensional change is about 3 times higher than Ni. The influence of graphite remained relatively small compared to the other factors.

All factors contributed to increase the apparent hardness. However, the Mo content has the highest effect with ~ 8 HRA versus ~ 3 HRA for the graphite content and 2 HRA or less for the Ni and copper content. It should be noted that Mo is very well distributed throughout the structure since it is pre-alloyed while the Ni and Cu are not evenly distributed in the structure since these elements are added as elemental powders. This may explain while the influence of Mo is higher than that of Ni and Cu on apparent hardness. Except for small differences, the UTS varied in a similar way as the apparent hardness. Again, the Mo content was the factor having the highest effect on UTS, with an increase of ~ 400 MPa between 0 and 0.85%Mo, which corresponds to 63% of the total variation in UTS measured. It is also interesting to observe that increasing the graphite content above 0.6% led to a drop in UTS. A similar effect was observed when increasing the Ni content above 3%. Cu content had a very limited effect on UTS, as it was the case for apparent hardness.

Finally, all factors contributed basically to reduce the elongation, the Mo and graphite content having the highest effect, 68% of total variation. The drop in elongation with Mo was mainly between 0 and 0.5%, a further increase in Mo content having only a very small effect on elongation.

As discussed previously, organic-bonded mixes exhibit a better compressibility than diffusion-alloyed mixes as shown in Figure Fig. 2. For instance, density is higher by ~ 0.05g/cm³ on average when a pressure of 540 MPa is applied (pressure required to press the reference mix to 7.0 g/cm³). This advantage can be used to further improve mechanical properties of parts. Based on equations calculated for each mix, the gain in apparent hardness, UTS and YS at 540 MPa.are about 0.5 HRA, 25 MPA and 15 MPA, respectively. On the other hand, the gain in elongation is negligible.

3. Optimisation of Mix Formulation

From an engineering point of view, the desired properties as well as cost are key elements to consider when designing an optimum formulation. One way to analyze both the effect of each factor on the properties and cost is by calculating a property-to-cost ratio and comparing it to that of the reference mix as indicated by the equation below:

$$P/C\ Index = (Prop_{Mix\ i} / Cost_{Mix\ i}) / (Prop_{Ref} / Cost_{Ref})$$

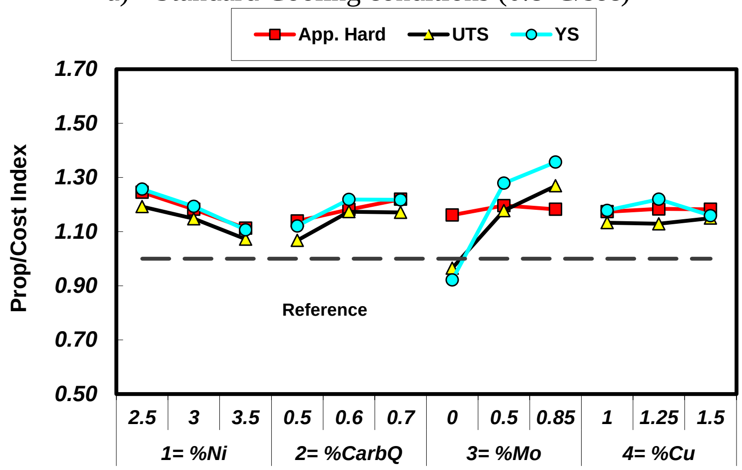
In this equation, all the cost related to the processing, alloying and additives as paid for the last quarter of 2013 (last data available) are considered. A P/C index value of 1 for a given characteristic and mix indicates that the property-to-cost ratio is equal to that of the reference. An increase of the P/C index value when raising the level of a given factor indicates that this factor allows increasing the property in a cost effective way. At the opposite, a reduction of the PC index value when the level of a given factor increases indicates that this factor does not improve the property in a cost effective way. Figure 4 illustrates the effect of each factor on the P/C index for hardness and static strength for slow-cooled (a) and fast-cooled (b) specimens after tempering. Elongation is not shown since all factors contributed to decrease it. Trends observed are very similar for both cooling conditions after tempering except maybe for the order of magnitude. It is interesting to note that in most cases, the P/C index is advantageous (>1) compared to the diffusion-alloyed reference powder.

Trends are summarized as follows:

- ⇒ Increasing elemental Ni content lowers the P/C index for all properties, indicating that adding Ni is not a cost effective way to increase sintered properties.
- ⇒ Increasing Mo level is highly beneficial for the static strength (TRS, UTS and YS). On the other hand, it has almost no effect on apparent hardness. Overall, even if costly, Mo allows increasing sintered properties in a cost effective way.
- ⇒ The beneficial effect of Mo on static strength cost ratio is higher under fast cooling conditions.

⇒ Increasing graphite level is beneficial for all properties when slow cooled conditions are used. However, 0.6% is the optimum level under fast cooling conditions for the UTS and YS.
⇒ Elemental Cu is basically neutral, P/C index remaining quite constant when Cu content is increased.
⇒ Except for graphite, none of the factors allows increasing hardness in a cost effective way, Mo and Cu being neutral.

a) Standard Cooling conditions (0.8°C/sec)



b) Fast Cooling conditions (1.3°C/sec)

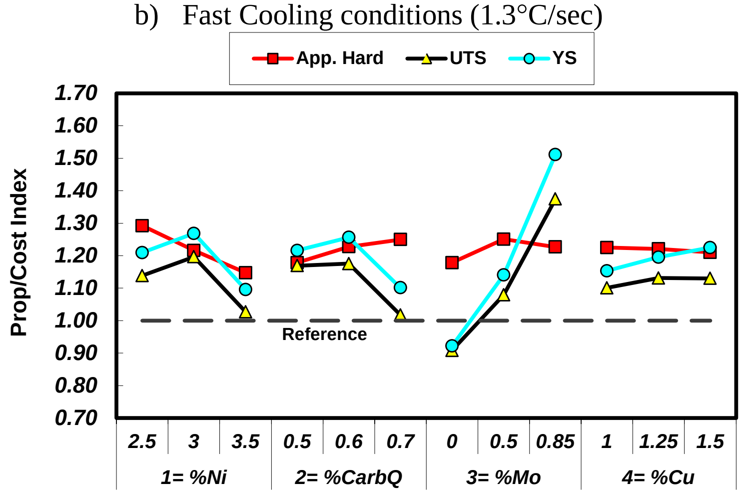


Figure 4. Effect of Ni, graphite, Mo and Cu content on the P/C Index (relative property to cost ratio) after tempering for (a) standard cooling conditions, and (b) fast cooling conditions.

From this analysis, it appears that maximizing the Mo level in the base powder and maintaining Ni level low is recommended to maximize sintered strength in a cost effective way. Graphite content of 0.6% is also preferable to maximize strength under fast cooling conditions. However, this may in turn negatively impact the elongation. Lowering graphite may then be required if a certain level of elongation must be reached. Cu does not appear as a key element except for dimensional change. Cu level will be mainly driven by the final part dimensions targeted.

An expert program was developed with the data acquired including the effect of each factor on the material cost. This program allows determining by iteration an optimized mix formulation meeting a desired set of sintered properties at the lowest possible cost. An example of the use of the program to develop a lean formulation equivalent to the reference diffusion-alloyed (DB48 with 0.6% graphite) for slow cooling rate conditions is given below. The following criteria were used in the model: ±34 MPa, -1/+3 HRA and ±0.02% vs the reference for TRS, hardness and dimensional change, respectively. No limit was applied on the elongation in this example.

The formulation proposed by the model was: ***AT4401 (0.85 Mo), 2.3% Ni, 1.15%Cu and 0.6% graphite***. A mix was then prepared according to this formulation using the organic-bonded process (binder-treatment technology applied to Ni and Cu only) and properties were compared to those of the reference. Specimens were pressed at 540 MPa, sintered under standard sintering/cooling conditions and tempered. The properties measured and estimated from the model are given in Table 3.

The proposed formulation gave equivalent or slightly higher sintered properties compared to the diffusion-alloyed powder. In general, a very good match was obtained between the measured and estimated properties, except maybe for UTS and elongation, which were over-estimated by the model for both the binder-treated lean powder and the diffusion-bonded reference powder. Such discrepancies are likely due to a difference in sintering/tempering conditions. Differences in the result obtained with the optimized material can also be explained by the fact that the DOE used did not allow to assess the effects of interactions. Interactions between factors can be important. However, the range studied for each factor was quite restricted, which should limit the interactions. Despite these differences, the model was helpful to design a leaner powder with similar or even slightly better properties than a reference at a much lower cost. The use of

Table 3. Estimated and measured properties for a lean organic-bonded and a diffusion-alloyed powder containing 0.5Mo-4Ni-1.5Cu. Conditions: 540 MPa, standard sintering and tempering.

Mix ID	Process	Chemistry	Cost Index	AD, g/cm^3	Flow, s/50g		S. Dens., g/cm^3	TRS, MPa	Hard., HRA (HRC)	DC vs green, %	UTS, MPa	YS, MPa	Elong., %
Ref	Diff-Alloyed	0.5Mo-4Ni-1.5Cu-0.6C	1.0	3.10	37	M *	6.99	1570	59.0 (18.2)	-0.22	725	517	1.1
						E *	6.98	1626	58.4 (17.1)	-0.21	788	520	2.2
F48 Lean	Org.-bonded	0.85Mo-2.3Ni-1.15Cu-0.6C	0.80	3.04	32	M *	7.05	1600	59.0 (18.2)	-0.20	757	659	0.5
						E *	7.03	1622	59.6 (19.3)	-0.22	906	636	1.3

* M stands for measured properties and E for properties estimated with the model

binder-treatment also contributes to increase density, and thus the properties, and reduce the cost of material while maintaining excellent Ni and Cu bonding. The proposed formulation represents a total cost saving of ~20% compared to the diffusion-alloyed powder.

DEVELOPMENT OF LEAN FD-0205 POWDERS

1. Experimental Procedures

A totally different experimental approach was used in this second study. A master diffusion alloyed powder containing three times the levels of Ni and Cu compared to the DB46 (0.5Mo-1.5Cu-1.75Ni) was produced in the laboratory and admixed with different levels of steel powders containing 0%, 0.55%, 0.85% and 1.50% pre-alloyed Mo to achieve the desired levels of Mo, Ni and Cu in the parts. This approach was used to maximize the bonding of Ni and Cu and likely limits the drawback on compressibility linked with the diffusion-alloyed process. DOE Taguchi

L9 plans were also used in this study to limit the experiments. Since 4 levels of Mo were investigated, Two Taguchi arrays were built as shown in Table 3. Mo content was varied from 0.35 to 0.75% in the first plan (T1) while it was varied from 0.35 to 1.25% in the second plan (T2). The final Mo concentration in the mix was achieved by admixing either ATOMET 1001 to lower the Mo content to 0.35% or admixing either ATOMET 4401 or ATOMET 4901 to increase the Mo content to 0.75 or 1.25%. ATOMET 4001 was also used in combination with the other base powders to achieve the desired levels of Ni and Cu. The levels of Ni varied from 0.4, 1.0 and 1.5%, which resulted in Cu content of 0.3, 0.75 and 1.1% respectively since the Cu/Ni ratio is fixed in the master powder (1.5/1.75). Cu is therefore not an independent variable and is therefore not considered as a separate factor in the Taguchi arrays. Finally, the last factor was Graphite content, which was fixed at 0.4, 0.5 and 0.6%.

Table 3. Levels used for the two Taguchi arrays

T1		
Mo, %	Ni, %	Graphite, %
0.35 (1001)	0.4	0.4
0.55 (4001)	1.0	0.5
0.75 (4401)	1.5	0.6

T2		
Mo, %	Ni, %	Graphite, %
0.35 (1001)	0.4	0.4
0.55 (4001)	1.0	0.5
1.25 (4901)	1.5	0.6

The chemistry of the 12 mixes required for this study is given in Table 4. All mixes were produced with a synthetic graphite KS15 and admixed with 0.75% zinc stearate. Some of the mixes were used for the two DOE arrays as indicated in Table 4. A cost index as described earlier was also calculated for these mixes. ATOMET DB46 mixed with 0.6% graphite was used as the reference (cost index = 1). Sintered properties were determined at 7.0 g/cm³ with the same methods described earlier. The samples were sintered in an industrial furnace at 1125°C for 20 minutes and cooled at a rate of 1.9°C/s in the range of 650 to 400°C. Half of the samples were evaluated in the as-sintered state while the other half was subjected to a tempering treatment at 205°C for one hour in air.

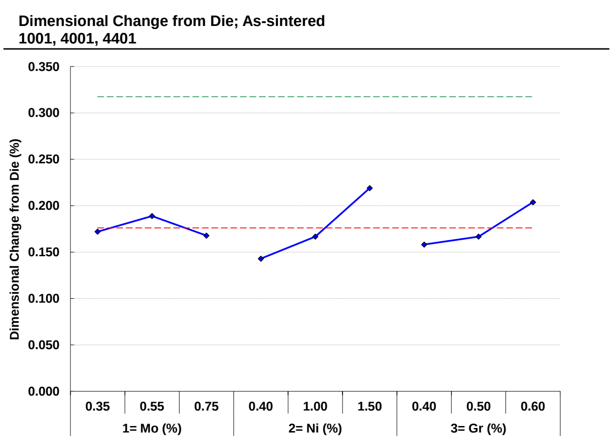
Table 4. Chemistry of the mixes used in this study

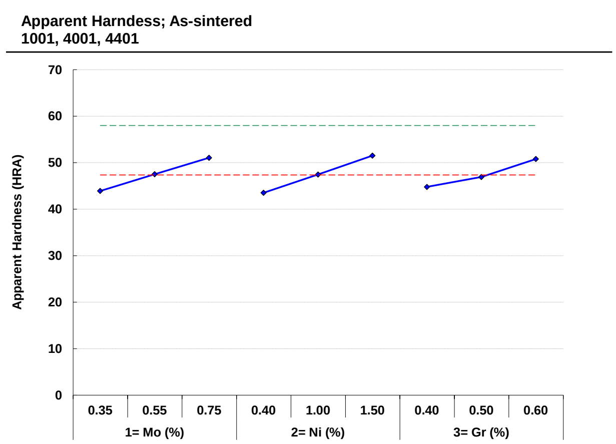
Mix #	Taguchi #	Mo, %	Ni (Cu), %	Graphite, %	Cost index
A	1, 2	0.35	1.5 (1.1)	0.4	0.74
B	1, 2	0.35	1.0 (0.7)	0.6	0.65
C	1, 2	0.35	0.4 (0.3)	0.5	0.55
D	1, 2	0.55	1.5 (1.1)	0.5	0.79
E	1, 2	0.55	1.0 (0.7)	0.4	0.69
F	1, 2	0.55	0.4 (0.3)	0.6	0.58
G	1	0.75	1.5 (1.1)	0.6	0.85
H	1	0.75	1.0 (0.7)	0.5	0.75
I	1	0.75	0.4 (0.3)	0.4	0.66
J	2	1.25	1.5 (1.1)	0.6	0.85
K	2	1.25	1.0 (0.7)	0.5	0.75
L	2	1.25	0.4 (0.3)	0.4	0.66

2. Effect of Mix Composition on Properties

The compressibility of all powders prepared in this study was very similar to the reference powder, indicating that the use of the master powder approach does not lead to any improvement in that regard. However, it should be pointed out that some gain could be obtained for larger production batches. The organic-bonded approach remains a better approach to maximize compressibility while maintaining very good bonding levels. On the other hand, all factors had very limited effect on compressibility, the overall range being of ~15 MPa (~1 tsi).

Figure 5 shows the effect of Mo, Ni and graphite on the sintered properties for the T1 plan. The flexural sintered strength as measured on TRS bars is not shown since it varies exactly like the UTS. In all graphs, the red dotted line represents the average value of all nine mixes included in the Taguchi array. The green dotted line is the value for an ATOMET DB46 reference mix containing 0.6% graphite sintered in the same conditions. In regards to dimensional change, Ni appears to have the biggest impact, an increase in Ni content resulting in larger growth. This appears somewhat strange at first sight since Ni is known to induce shrinkage during sintering. However, as mentioned earlier, an increase in Ni content also resulted in an increase in Cu content. This increase in dimensional change as observed on Figure 5 is likely linked to the increase in Cu content. Indeed, the previous section clearly showed that Cu has a higher effect on dimensional change than Ni, at least three times.





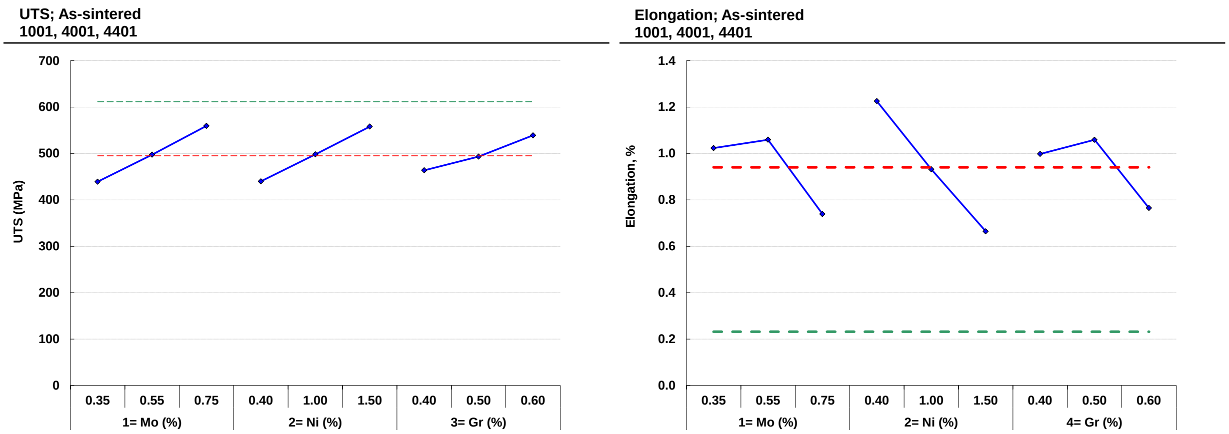


Figure 5. Effect of Mo, Ni-Cu and graphite on sintered properties of mixes containing ATOMET 1001, 4001 and 4401 (Taguchi T1).

The UTS and apparent hardness show similar tendencies. Indeed, as expected, an increase in all alloying elements resulted in an increase in mechanical properties. The impact of increasing the Mo content from 0.35% to 0.75% was very similar to that of increasing the Ni content from 0.4 to 1.5% (and Cu from 0.3 to 1.1%). Finally, increasing alloying elements resulted in a drop in elongation. The effect of graphite is however statistically very small. Varying the Ni content had the strongest effect on elongation. Again, the effect of copper should also be taken into account. The previous study showed that increasing the copper content reduces the elongation. In this case, it is not possible to differentiate which factors contributed the most to the drop in elongation. It should be noted that the elongation of the DB46 reference was significantly lower than the other mixes. Such a low value can be likely explained by the very high cooling rate used in this experiment. However, the value is not abnormal in view of the results obtained for the other materials.

Figure 6 shows the same analysis for the UTS and apparent hardness for the T2 plan for a wider range of Mo content (0.35-1.25% Mo). The results obtained with plan T1 are also shown for comparison. Very similar trends were obtained for both plans. Indeed, the effect of Ni and graphite on UTS and hardness were almost identical, suggesting that the two Taguchi plans are complementary and interactions are very limited. UTS and apparent hardness increased continuously with the Mo content, the values reached at 1.25%Mo being superior to those obtained at 0.75%. Regardless of price, it appears that increasing Mo up to 1.25% is beneficial to the mechanical properties. However, it should be kept in mind that the scale is not proportional to the concentration in Figure 6. Since the two Taguchi plans are complimentary, it is then possible to combine both results to evaluate the effect of Mo on properties as shown in Figure 7 for the UTS and YS. Both UTS and YS increase linearly between 0.35 and 0.75% Mo but then tend to flatten above 0.75%. This indicates that a level of 1.25% may be overdesigned, the optimum Mo content being somewhere between 1.0 and 1.1%.

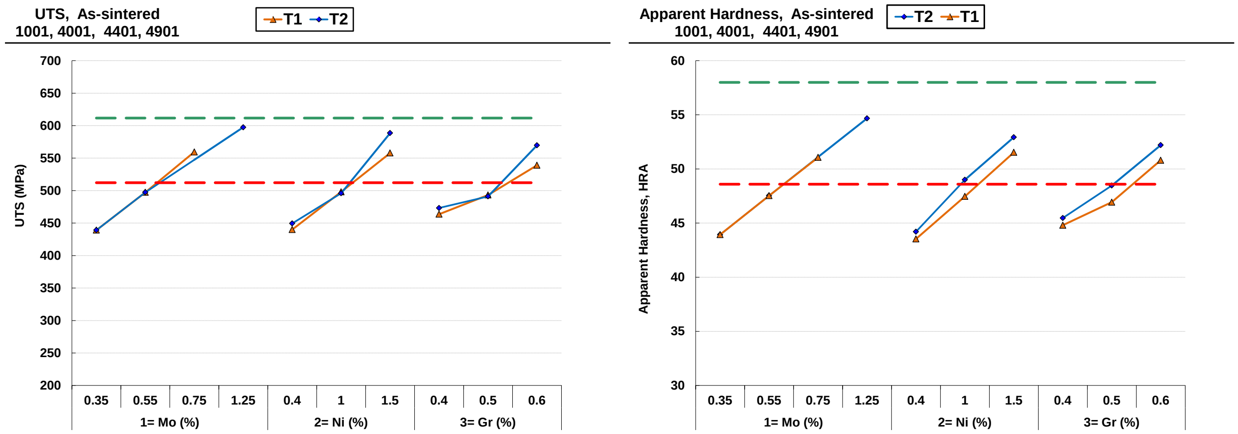


Figure 6. Effect of Mo, Ni and graphite on sintered properties of mixes containing ATOMET 1001, 4001 and 4901 (Taguchi T2)

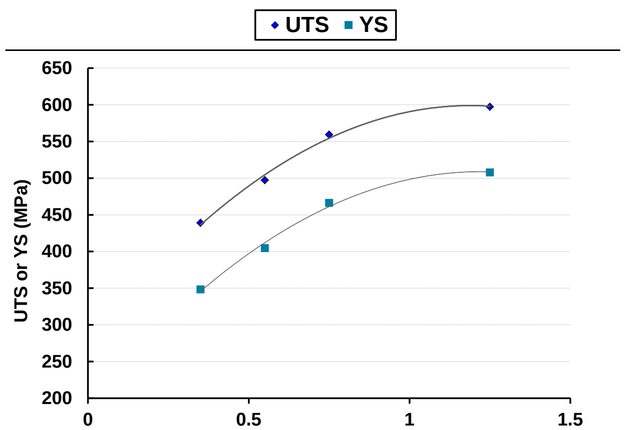


Figure 7. Impact of Mo content on TRS (T1 and T2 combined).

3. Optimization of Mixes Formulation

Figure 8 illustrates the property to cost ratio as measured according to the equation given in the previous section. The apparent hardness, UTS and Yield strength are illustrated. The results achieved for the 4 levels of Mo were plotted since the two plans matched very well. As it was the case for the previous study, it is seen that increasing the Mo content is beneficial on the UTS, YS and hardness from the cost point of view while increasing the Ni and Cu is rather detrimental, i.e. it is not cost effective. It is interesting to note that such a trend is obtained with two different approaches. The yield strength to cost index is lower than the UTS-to-cost index mainly because of the lower levels of alloying elements and graphite content versus the reference, which resulted in lower yield strength but much higher elongation as shown in figure 5. Finally, increasing the graphite content is highly beneficial on all properties based on the Prop/Cost indexes. The cost of graphite remains low compared to the other alloying elements and is very effective to increase the hardenability.

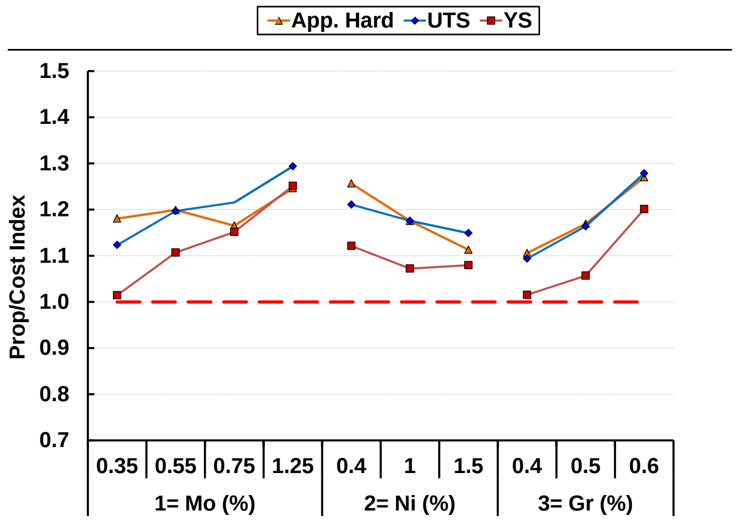


Figure 8. Effect of Mo, Ni and graphite content on the Property-to-cost Index for as-sintered apparent hardness, UTS and YS (T1 and T2 combined).

Equations were drawn separately for each Taguchi plan and a model was built to predict each property as well as the cost of the predicted system as a function of the three parameters studied (Mo, Ni (Cu) and graphite). The model was then used to predict optimum formulations matching the properties of ATOMET DB46 reference mixes at the lowest possible cost. Two different formulations with DB46 were investigated; one with 0.4% graphite and the other with 0.6% graphite. Limits of ± 25 MPa, -2.5/+5 HRA and -35/+75 MPa were set in the program for TRS, Hardness and UTS respectively. No limit was set for the dimensional change as most mixes were significantly more negative than the reference mixes. New tools would have to be designed in order to use such mixes. It should be noted that dimensional change could be matched by adding elemental copper to the mix. Two materials were developed for each reference, one based on the T1 plan (0.35-0.75% Mo) and the other based on the T2 plan (0.35-1.25% Mo). The optimum mix formulations matching the as-sintered properties of the two references are given in Table 4.

Table 4. Mix chemistries matching properties of the references mixes in the as-sintered conditions

Reference matched	Array	Mix	Mo, %	Ni (Cu), %	Graphite, %	Cost Index
DB46 – 0.4% gr.	T1	Mix 1-1	0.75	0.88 (0.66)	0.6	0.77
	T2	Mix 1-2	1.25	0.42 (0.32)	0.6	0.77
DB46 – 0.6% gr.	T1	Mix 2-1	0.75	1.12 (0.85)	0.6	0.81
	T2	Mix 2-2	1.25	0.65 (0.49)	0.6	0.80

For the two plans, the program always maximized the Mo content since this element is the most cost effective element in regards to mechanical properties. Even though Mo alone is more expensive, its positive impact on properties was greater than Ni and Cu as shown in the previous study. It should be noted that intermediate level of Mo could have been a better solution in term of cost, likely around 1 - 1.1%. However, we did not allow the program to select intermediate Mo levels. The program also maximized the graphite content.

Laboratory mixes with the optimum formulations given in Table 4 were produced and evaluated under the same sintering conditions used in this study. It should be noted that all mixes were produced with graphite KS15 and 0.75% Zn stearate. Properties in the as-sintered state are reported in Table 5. Properties achieved with the optimum formulations were very close to those of the references and matched very well the estimated properties calculated with the model. The results confirmed the efficiency of this approach to develop leaner versions.

Table 5. As-sintered properties of optimum mixes developed and ATOMET DB46 reference mixes

Mix	Dim.Ch. vs. Die, %	TRS, MPa	App. Hardness, HRA	UTS, MPa
1-1	0.18	1112	54	590
1-2	0.15	1111	54	594
REF 1 (DB46 0.4%)	0.3	1136	51	562
2-1	0.20	1160	56	615
2-2	0.17	1159	56	605
REF 2 DB46 0.6%	0.3	1181	58	609

In summary, the trends observed with a master powder approach were very similar to those observed in the previous study with a binder-treatment approach. Indeed, both studies showed that maximizing the Mo content while keeping Cu and Ni content low were highly beneficial for the properties and cost of FD-0205 and FD-0405 powder systems. Results also suggest that the model developed with the master powder approach could also be used for regular and binder-treated mixes equivalent to FD-0205 system. However, a validation of this was not carried out in the present program.

CONCLUSIONS

The results of two studies carried out to better understand the influence of Mo, Ni, Cu and graphite contents on the properties and cost of systems similar to FD-0205 and FD0405 and to develop tools to optimize powder formulations were presented. The major conclusions of these studies are summarized below:

- ⇒ A significant gain in density is obtained when using organic-bonded powders instead of diffusion-alloyed powder, which reached about 0.05 g/cm³ at 540 MPa.
- ⇒ Using a master diffusion-alloyed powder approach did not allow improving compressibility.
- ⇒ Mo was found to be the element having the strongest effect on sintered properties in both studies and increasing its content in steel powder is a cost effective way to improve sintered properties. Its effect appeared greater under fast cooling conditions for high Ni content.
- ⇒ On the contrary, Ni did not allow increasing the mechanical properties in a cost effective way. In other words, increasing its content has more effect on price than on properties. It is thus not recommended to increase its content.
- ⇒ The effect of copper was mainly neutral while graphite content was beneficial for most of properties.

- ⇒ All factors had a detrimental effect on ductility.
- ⇒ Models allowing determination of optimized formulations as a function of green and sintered performance and cost were developed from the data generated in these studies.
- ⇒ A leaner organic-bonded version equivalent to FD-0405 diffusion-alloyed powder was developed with the following formulation: 0.85% pre-alloyed Mo, 2.3% Ni, 1.15% Cu and 0.6% graphite. A cost saving of ~ 20% is achieved with such a formulation.
- ⇒ Increasing the Mo content up to 1.25% was beneficial to the properties of FD-0205 type materials. However, the effect of Mo tends to flatten out between 0.85 and 1.25%, suggesting that the optimum Mo content should be around 1.0 to 1.1%.
- ⇒ The use of a master diffusion-alloyed powder diluted with Mo base powders allowed achieving properties similar to the FD0205 formulations but with lower levels of Ni and Cu.
- ⇒ The cost saving of leaner versions with properties similar to as-sintered ATOMET DB46 with 0.4 and 0.6% graphite varied between 19 and 23%.

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