# EFFECT OF DENSITY AND MIX FORMULATION ON SINTERED STRENGTH AND DIMENSIONAL STABILITY OF 0.85% Mo LOW ALLOY STEEL POWDERS

**C. Gélinas and S. St-Laurent**

**Quebec Metal Powders Limited,**
**1655 Marie-Victorin, Sorel-Tracy, Québec, Canada, J3R 4R4**

## ABSTRACT

The growth of the P/M industry is highly focused on applications requiring high mechanical strength. For these applications, an improved dimensional control of the P/M components is also required in order to reduce or avoid post-sintering treatments and reduce cost. Low alloy steel base powders containing alloying elements such as manganese, molybdenum, nickel or chromium are widely used for such applications. In particular, pre-alloyed Mo steels are very interesting materials for high density applications since molybdenum is an efficient strength enhancer having little detrimental effect on the compressibility. Elemental powders such as graphite, copper and nickel are also usually admixed to increase the hardenability and achieve the targeted sintered properties without sacrificing too much on the compressibility. Of course, the concentration, the type and the nature of these additives also influence the dimensional stability.

A study was conducted to evaluate and quantify the effect of elemental additives such as copper, nickel and graphite, and density on the sintered properties of parts made from a water atomized steel powder pre-alloyed with 0.85% Mo. The effect of mix composition and part thickness on the dimensional stability of ring specimens was also evaluated.

## INTRODUCTION

Over the last few decades, the development of new materials and the improvement of manufacturing processes have led to a significant increase in the level of strength that can be reached in P/M sintered parts. New demanding applications requiring high mechanical strength are being successfully developed and markedly contribute to the growth of the P/M industry. From the material side, this success is mainly attributable to the flexibility that P/M brings to steel powder production processes. In fact, P/M technology opens the door to a wide range of compositions by varying the concentration of the alloying elements added to the melt or in the powder mix as elemental additives. This, in turn, enables a more detailed tailoring of desired microstructures and mechanical properties. For instance, for applications requiring high density and high mechanical strength, pre-alloying steels with molybdenum is very interesting as this element is an efficient strength enhancer which has little detrimental effect on compressibility as compared to other alloying elements such as Cr, Mn and Ni [1]. Moreover, in order to further increase hardenability and achieve targeted sintered properties without sacrificing too much on compressibility, elemental alloying additives such as graphite, copper and nickel can be added to the mix. It is also common practice to bind these admixed additives to the steel powder particles in order to reduce segregation and dusting and also improve the flowability of mixes thus improving die filling and homogeneity of the powder mix within the die cavity.

Another important aspect to consider to further increase the usage of P/M materials is the dimensional stability of the P/M components during the sintering treatment. There are numerous merits to a better dimensional change control, amongst which:

- Reduction of the manufacturing costs by avoiding post sintering sizing and machining steps.
- Increased usage of high hardness materials that cannot be machined or calibrated to adjust the final size after sintering.
- Reduction of scrapped parts that do not meet dimensional specifications.

In a recent study [2], it was shown that the particle size of the graphite and copper additives has a significant impact on the dimensional stability of parts pressed from binder-treated FLNC-4405 mixes. For instance, the use of fine copper and graphite additives resulted in much smaller dimensional variations and distortion within and between parts. In continuation to this work, the effect of mix composition and part thickness on the dimensional stability of parts made from a steel powder pre-alloyed with 0.85% Mo is evaluated in the present study. The effect of elemental copper, nickel and graphite additives and density on the sintered properties is also evaluated and quantified.

## EXPERIMENTAL PROCEDURE

A water-atomized FL-4400 low alloy steel powder containing 0.15% Mn and 0.85% Mo, ATOMET 4401, was used as the base powder in this study. For the first part of the study, mixes containing 0.75% wax were prepared with various amounts of graphite, copper and nickel additives. The composition of the mixes is given in Table I. Note that the average carbon content measured in the specimens after sintering was about 0.31%, 0.50%, 0.69% and 0.89% for the mixes containing 0.4%, 0.6%, 0.8% and 1% graphite respectively.

Standard transverse rupture strength specimens and flat tensile bar specimens (dog bones) were pressed at three different densities: 6.7, 6.9 and 7.1 g/cm$^3$. Specimens were sintered in a mesh belt furnace at 1120°C for 25 minutes in a $N_2$/10% $H_2$ atmosphere with a post-sintering cooling rate of about 0.65°C/s in the temperature range of 650°C to 400°C. Half of the specimens were characterized as-sintered while the other half were tempered at 205°C in air for 60 minutes. Transverse rupture strength, apparent hardness and dimensional change from die size were measured on the TRS bars according to MPIF Standards 41, 43 and 44 respectively while tensile properties (yield strength, ultimate tensile strength and elongation) were determined on dog bones according to MPIF Standard 10.

In the second part of the study, the dimensional stability or distortion was evaluated for two binder-treated compositions made with ATOMET 4401 as base steel powder. One mix had a low level of additives while the other had a much higher level of additives. The two compositions are given in Table II.

Table I. Composition (wt %) of the ATOMET 4401 based mixes used in this study.

| Mix # | Graphite | Copper | Nickel |
|---|---|---|---|
| 1<br>2<br>3<br>4 | 0.4<br>0.6<br>0.8<br>1.0 | 1 | 0 |
| 5<br>6<br>7<br>8 | 0.4<br>0.6<br>0.8<br>1.0 | 1 | 2 |
| 9<br>10<br>11<br>12 | 0.4<br>0.6<br>0.8<br>1.0 | 1 | 4 |
| 13<br>14<br>15 | 0.4<br>0.8<br>1.0 | 0 | 0 |
| 16<br>17<br>18 | 0.4<br>0.8<br>1.0 | 2 | 0 |

Basically, the mix compositions differ by their nickel and graphite contents which vary respectively from 1.5% and 0.4% for the low additive mix to 4.0% and 0.8% for the high additive mix.

Table II. Composition (wt %) of the two ATOMET 4401 based mixes used for the study on the dimensional stability.

| Identification | Low content (3.15%) | High content (5.50%) |
|---|---|---|
| Copper<br>Nickel<br>Graphite | 1.25<br>1.50<br>0.40 | 1.20<br>3.50<br>0.80 |
| Binder-lubricant | 0.80 | 0.80 |

Thin wall rings were selected for the dimensional stability study since this type of specimens is more susceptible than TRS bars to show distortion during sintering. Two series of rings 1.3 cm and 2.3 cm height (0.5" and 0.9") with an outside and inside diameter of 5.1 cm and 4.3 cm (2.0" and 1.7") were compacted on a 100 Ton press with a floating die to a density of 7.0 g/cm$^3$. The corresponding weight for these parts was about 55 g and 100 g respectively. The position of rings with respect to the tooling was clearly identified in order to assure that the measurements were done according to the same reference point. Rings were sintered under the same conditions than the standard TRS bars (25 min at 1120°C in a $N_2$/10%$H_2$ atmosphere) and tempered at 205°C in air for 60 minutes. The rings were sintered in batches of five per tray with the bottom side facing down. The top and bottom outside diameters in the green and sintered states were measured at two different positions along the circumference: 0° and 90° from the reference point. A positioning fixture was used with a high precision digital indicator with a resolution of 0.0025 mm (0.0001") in order to improve the accuracy and reproducibility of the measurement. The diameters were measured 0.25 cm below the top surface and 0.25 cm above the bottom surface. The mean top and bottom outside diameters were calculated from these values. The dimensional changes from green size were calculated from these mean diameters. For the purpose of this work, the parts distortion or dimensional stability was evaluated by calculating the difference in dimensional change between the top and bottom of the rings.

## RESULTS AND DISCUSSION

The mechanical properties are first presented for the base Mo pre-alloyed P/M steel with different carbon and copper contents pressed at a density of 6.9 g/cm³. The addition of nickel to further increase the mechanical properties of this material system containing 1% Cu is then presented. A section follows where the effect of density on the properties of few selected materials is discussed. Finally, the effect of the amount of additives and part thickness on the dimensional stability of rings is presented and discussed.

### *Effect of carbon and copper contents on properties of 0.85% Mo pre-alloyed P/M steels.*

In the following section, the results obtained with the 0.85% Mo pre-alloyed powders admixed with graphite and copper and pressed to 6.9 g/cm³ are presented. It is worth mentioning that identical trends were obtained at 6.7 and 7.1 g/cm³. The effects of combined carbon and copper contents on the TRS, apparent hardness and DC from die size are presented in Figure 1 for sintered and tempered specimens. As expected, the TRS and the apparent hardness both increase with carbon and copper contents. For specimens containing no copper or 1% Cu, the TRS and apparent hardness increase linearly with the carbon content and tempering has little effect. However, for specimens containing 2% Cu, a different behavior is seen. In the as-sintered condition, the TRS increases with the carbon content up to about 0.65% where it reaches a maximum of 1310 MPa. A further increase of the carbon content leads to a drop in TRS down to 1140 MPa at 0.9% C. This is attributed to an increase in the proportion of martensite in the microstructure as the carbon content increases. Tempering at 205°C is very beneficial on TRS while it decreases slightly the apparent hardness for carbon content above 0.5%. For instance, a TRS of about 1380 MPa is obtained at 0.9% C on tempered specimens.

Regarding the DC, different behaviors are observed as a function of the level of copper. The DC from die size increases with the carbon content in the copper free material. At 1% Cu, the DC is almost independent of the sintered carbon level, the difference being only -0.04% between 0.3% and 0.9% C. However, at 2% Cu, the DC drops drastically from +0.45% to +0.23% between 0.3% and 0.7% C and then tends to stabilize between 0.7% and 0.9% C. In fact, at low carbon content the effect of the melting of copper at about 1085°C during sintering shows up clearly with a large increase of the DC caused by its penetration in the steel grain boundaries. The growth increases with the copper content. However, at high carbon content, the copper growth is reduced because carbon increases the dihedral angle of liquid copper and inhibits its penetration in the iron. As a result, at 0.75% sintered carbon and above, no significant difference in DC is seen by varying the copper content from 0 to 2%.

The effects of combined carbon and copper contents on the tensile properties are illustrated in Figure 2 for sintered and tempered specimens. The behavior of the UTS is identical to that of the TRS. Indeed, at 0% and 1% Cu, the UTS increases with the combined carbon and copper contents and a tempering at 205°C has little effect. At 2% Cu, in the as-sintered condition, the UTS increases first with the carbon content, reaches a maximum of 720 MPa at about 0.65% C and then decreases with a further increase of the carbon content. As for the TRS, a tempering at 205°C is beneficial for the UTS at 0.5% C and above. For instance, for specimens containing 0.9% C, the UTS increases from 640 MPa in the as-sintered state to 750 MPa after tempering, giving a gain of about 110 MPa. In fact, after tempering, a constant UTS value of about 750 MPa is reached for samples containing between 0.5 and 0.9% C. Finally, the YS increases with the carbon content and the addition of copper has also a beneficial effect. However, in the as-sintered condition, similar values of YS are achieved at 1 and 2% Cu. The beneficial effect of adding 2% Cu on YS appears only after the tempering treatment with a gain of about 60 MPa for samples containing between 0.6 and 0.9% C. Values in the range of 550 to 575 MPa are obtained after tempering for carbon levels between 0.7 and 0.9%.

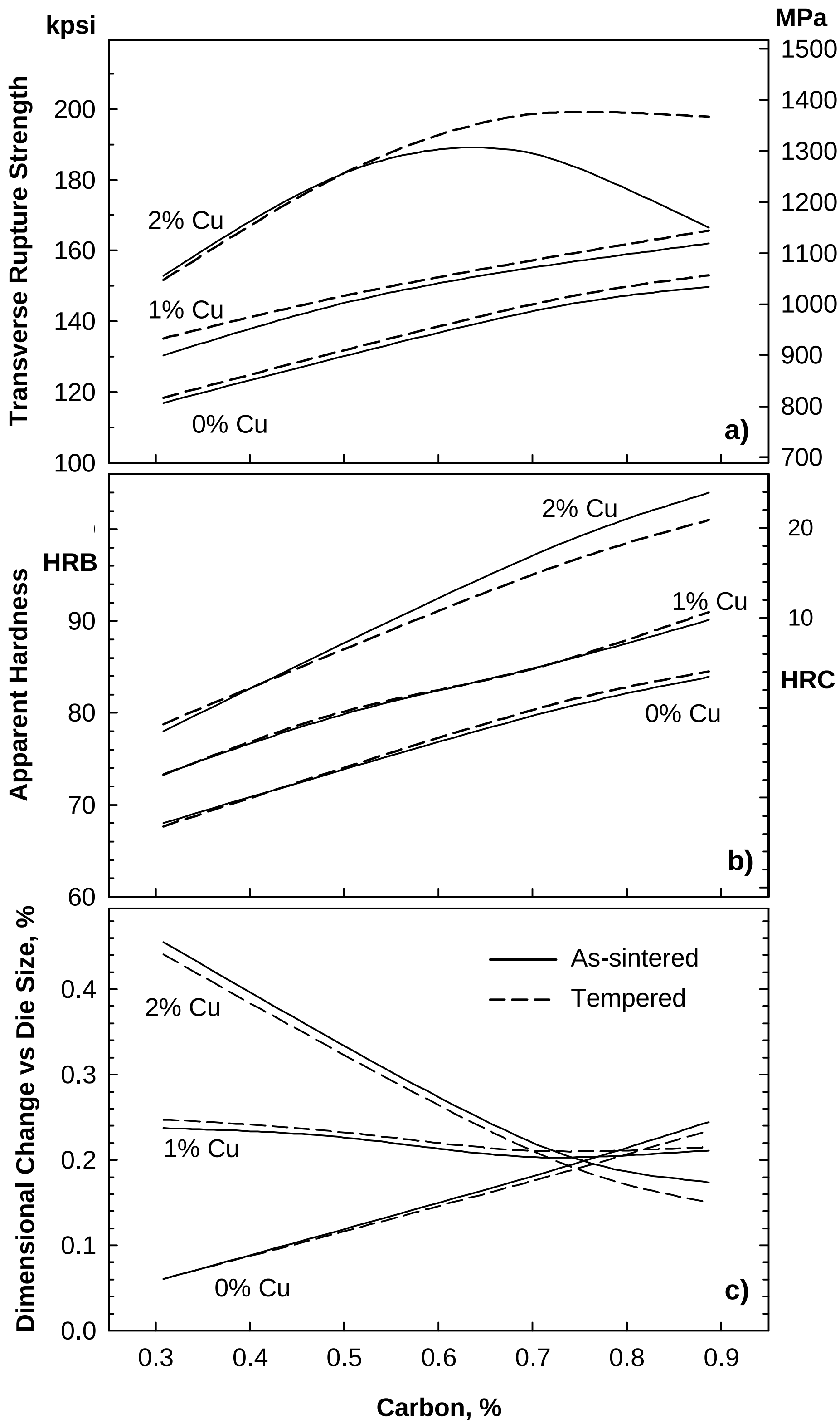


Figure 1. Effect of combined carbon and copper contents on properties of 0.85% Mo pre-alloyed P/M steels pressed to 6.9 g/cm³ after sintering (1120°C/25 min) and after tempering (205°C/60 min): a) transverse rupture strength; b) apparent hardness and c) dimensional change from die size.

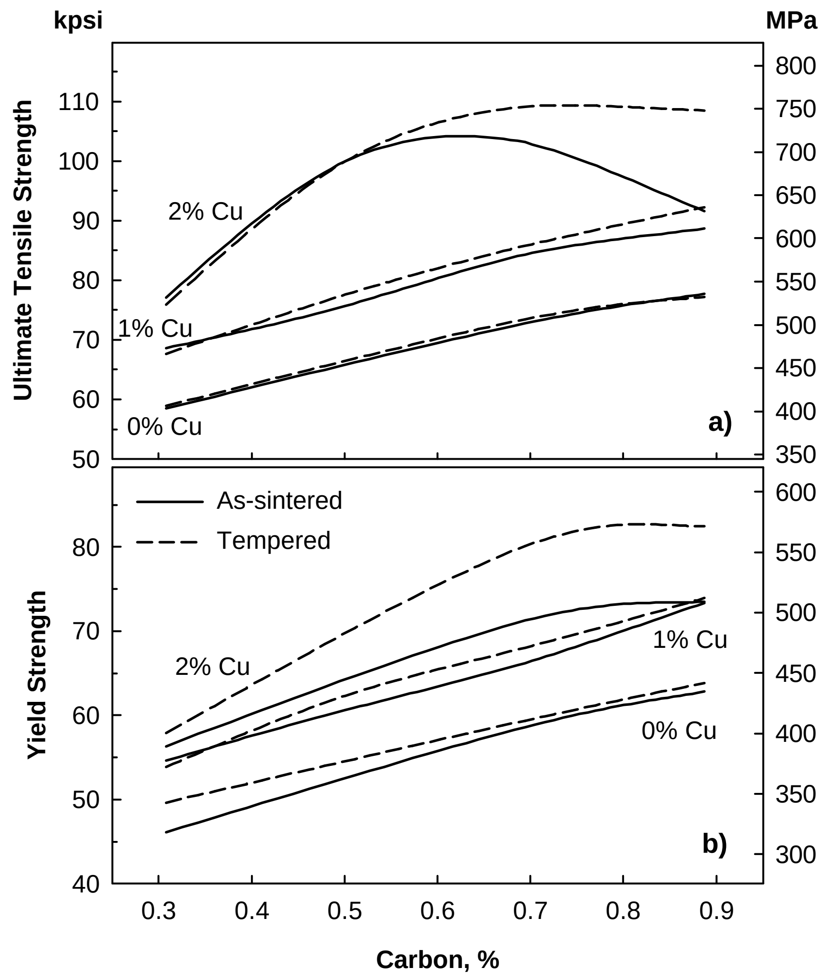


Figure 2. Effect of combined carbon and copper contents on tensile properties of 0.85% Mo pre-alloyed P/M steels pressed to 6.9 g/cm³ after sintering (1120°C/25 min) and after tempering (205°C/60 min):
a) ultimate tensile strength and
b) yield strength.

Regarding the elongation, values below 1.8% were obtained for all the mixes evaluated in this study. The maximum values were obtained at a low carbon content and decreased with an increase of the carbon content. It should be noted that the density, copper and nickel had only a minute effect on elongation for the range investigated. However, the elongation is known to increase exponentially with the density. Thus significant improvement in elongation is expected for densities above 7.1 g/cm³ with this material system.

***Effect of carbon and nickel contents on properties of 0.85% Mo pre-alloyed P/M steels with 1% Cu.***

In this section, the influence of admixing different levels of Ni and graphite on the sintered and tensile properties of a 0.85% Mo pre-alloyed steel-1% admixed Cu material is presented. Results shown in this section were obtained on specimens pressed to 6.9 g/cm³. Identical trends were obtained at 6.7 g/cm³ and 7.1 g/cm³. It should be noted that the copper level selected for this study is the one giving the most stable DC with respect to the carbon content, as shown in Figure 1c and previously discussed. The effects of varying the combined carbon and nickel contents on the TRS, apparent hardness and DC from die size after sintering and after tempering are presented in Figure 3. In specimens containing no nickel, TRS and apparent hardness increase with the carbon content and tempering has little effect. At 2% and 4% Ni, in the as-sintered condition, the TRS increases first with the carbon content, reaches a maximum at about 0.45% C and then decreases significantly with a further increase in carbon content. The maximum TRS obtained is about 1340 MPa and 1450 MPa for specimens containing 2% Ni and 4% Ni respectively. The

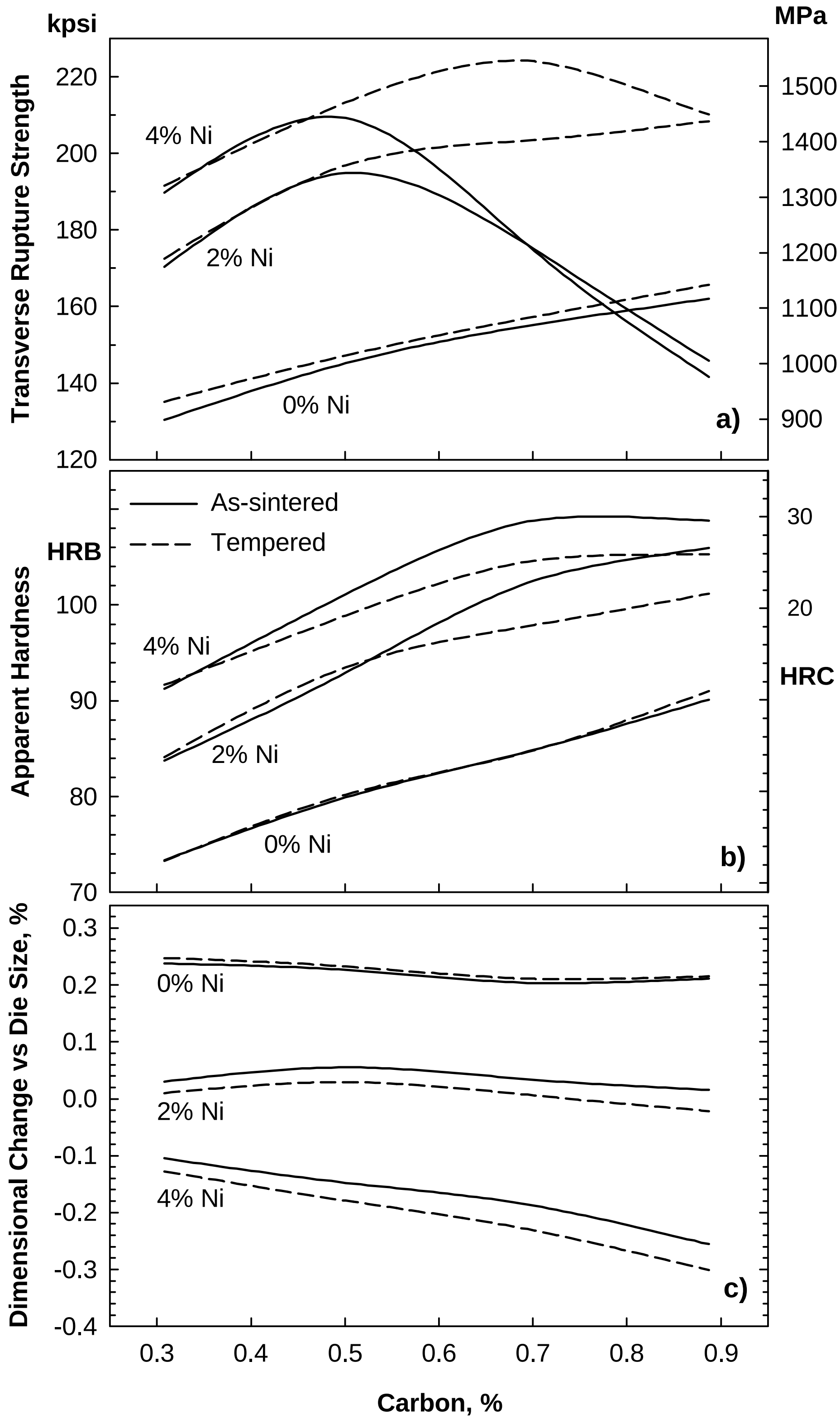


Figure 3. Effect of combined carbon and nickel contents on properties of 0.85% Mo pre-alloyed P/M steels with 1% Cu pressed to 6.9 g/cm³ after sintering (1120°C/25 min) and after tempering (205°C/60 min): a) transverse rupture strength; b) apparent hardness and c) dimensional change from die size.

apparent hardness also increases with an increase in carbon content but levels off at about 0.7% C. Apparent hardness in the range of 25 to 30 $R_C$ is achieved between 0.7 and 0.9% C. The drop in TRS observed at 2 and 4% Ni when the level of carbon exceeds 0.45% can be explained by an increase in the proportion of martensite with the carbon content as indicated by the high values of apparent hardness reached. It is also known that nickel, which diffuses in the solid state and does not melt like copper under normal sintering conditions, promote the formation of Ni-rich austenite areas.

Tempering has clearly a beneficial effect on the TRS for specimens containing 2 and 4% Ni and more than 0.45% C. Indeed, it is seen at 2% Ni that the TRS after tempering increases continuously with the carbon content up to about 1430 MPa at 0.9% C. This represents a gain in TRS of 430 MPa as compared to the TRS value achieved in the as-sintered state. Tempering has a similar influence at 4% Ni. However, it is seen that the TRS reaches a maximum of about 1540 MPa at 0.7% C and then decreases slightly with a further increase in carbon content. As a result, similar TRS values are obtained at 0.9% C for specimens containing 2 and 4% Ni. The apparent hardness at high carbon contents decreases by about 5 $R_C$ after the tempering. This behavior in TRS and hardness for the two materials containing nickel is typical of sinter hardened materials such as ATOMET 4601 (0.55% Mo, 0.2% Mn and 1.8%Ni), ATOMET 4701 (1% Mo, 0.45% Mn, 0.9% Ni and 0.45%Cr) and 4801 (0.5% Mo, 0.2% Mn and 4.0 % Ni) [3, 4, 5].

The addition of nickel has a significant effect on DC which becomes more negative as the nickel content increases. Typically, each one percent increment of nickel in the mix leads to a variation in DC of -0.08% to -0.12% depending on the amount of carbon. There are two reasons explaining the influence of nickel on dimensional change. First, nickel promotes diffusion and causes more shrinkage at the isothermal sintering temperature. Secondly, nickel is an austenite stabilizer and reduces thus the expansion during the $\gamma \rightarrow \alpha$ phase transformation [6]. It is interesting to point out that the DC is almost independent of the carbon content at 0% and 2% Ni while it decreases from -0.10% to -0.25% when the carbon content is increased from 0.3% to 0.9% at 4% Ni. Therefore, in terms of dimensional stability, a mix containing 2% Ni should be more robust to carbon segregation that may occur during powder handling and transfer to the press. Tempering has no effect on the DC for the material without nickel and leads to a decrease in DC of about 0.03% for materials containing 2 and 4% Ni. This variation in DC after tempering at 205°C is related to a change in the structure of the martensite from body-centered tetragonal to hexagonal structure that causes shrinkage.

The effects of varying the combined carbon and nickel contents on the tensile properties after sintering and tempering are illustrated in Figure 4. Again, the behavior of the UTS is identical to that of the TRS. Increasing the level of nickel has a beneficial effect on UTS in both the as-sintered and tempered conditions. However, for the 2% and 4% Ni containing materials in the as-sintered condition, the UTS increases first with the carbon content, reaches a maximum at about 0.45% to 0.55% C and then drops as the amount of martensite in the structure significantly increases. The maximum UTS obtained is about 730 MPa at 0.55% C and 2% Ni and 800 MPa at 0.45% C and 4% Ni. After tempering, the UTS of the 2% Ni material increases continuously with the carbon content up to about 810 MPa at 0.9% C, which corresponds to a gain of 240 MPa with respect to the as-sintered condition. The UTS of the 4% Ni material increases also, reaches a maximum value of about 880 MPa at 0.7% C and then slightly drops with a further increase in the carbon content. Very similar UTS values are obtained at 0.9% C for the materials with 2% and 4% Ni. Regarding the YS, it increases linearly with the carbon content in the absence of nickel and the tempering has little effect. At 2% and 4% Ni, a maximum value is reached at an intermediate level of carbon in the as-sintered condition : about 520 MPa at 0.7% C and 2% Ni and 550 MPa at 0.55% C and 4% Ni. It should be noted that the maximum YS is slightly offset as compared to the UTS. After tempering, YS for specimens containing 2% Ni increases with the carbon content and levels off at about 550 MPa at 0.7% C. For the 4% Ni material, the tempering has only a little effect, the

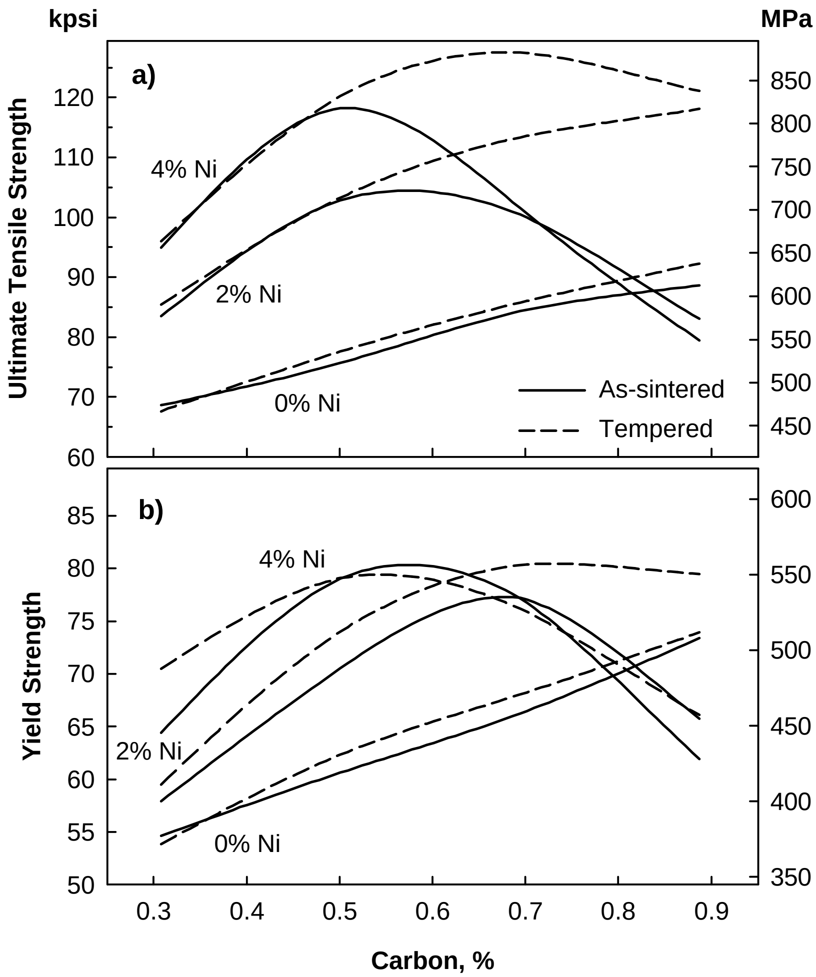


Figure 4. Effect of combined carbon and nickel contents on tensile properties of 0.85% Mo pre-alloyed P/M steels with 1% Cu pressed to 6.9 g/cm³ after sintering (1120°C/25 min) and after tempering (205°C/60 min): a) ultimate tensile strength and b) yield strength.

YS remaining very similar to that achieved in the as-sintered condition with a maximum of about 550 MPa between 0.5% and 0.6% C. This is likely attributable to the presence of Ni-rich retained austenite areas which are little affected by a tempering at 205°C. Regarding the elongation at 6.9 g/cm³, it varies from 0.5% to 2.0%. Typically, it decreases as the level of carbon increases and the nickel content has no significant effect. Elongation slightly improves after a tempering treatment.

It is worth outlining that the differences in the static properties after sintering and tempering are not significant between 2% and 4% Ni. In fact, it appears that the best overall properties with this 0.85% Mo pre-alloyed steel-1% Cu material system are achieved by adding 2% Ni: stable dimensional change with respect to the carbon content and high UTS and YS values. For the static mechanical properties, there is thus no real advantage of using more nickel. However, if dynamic properties are sought, such as impact and fatigue strength, it has already been demonstrated that values increase with the nickel content [7, 8].

***Effect of density on properties of 0.85% Mo pre-alloyed steel powders admixed with C, Cu and Ni.***

In the following section, the effect of density is illustrated and discussed for three materials based on the FL-4405 (0.85% Mo pre-alloyed steel with 0.7% sintered carbon). The mixes are: the base FL-4405 powder, the FL-4405 admixed with 1% Cu and the FL-4405 admixed with 1% Cu and 2% Ni (FLNC-4405). These levels of copper and nickel addition were selected because they produce materials with a dimensional change almost independent of the carbon content. This is an interesting feature when dimensional stability is a critical issue or a key characteristic for a given application.

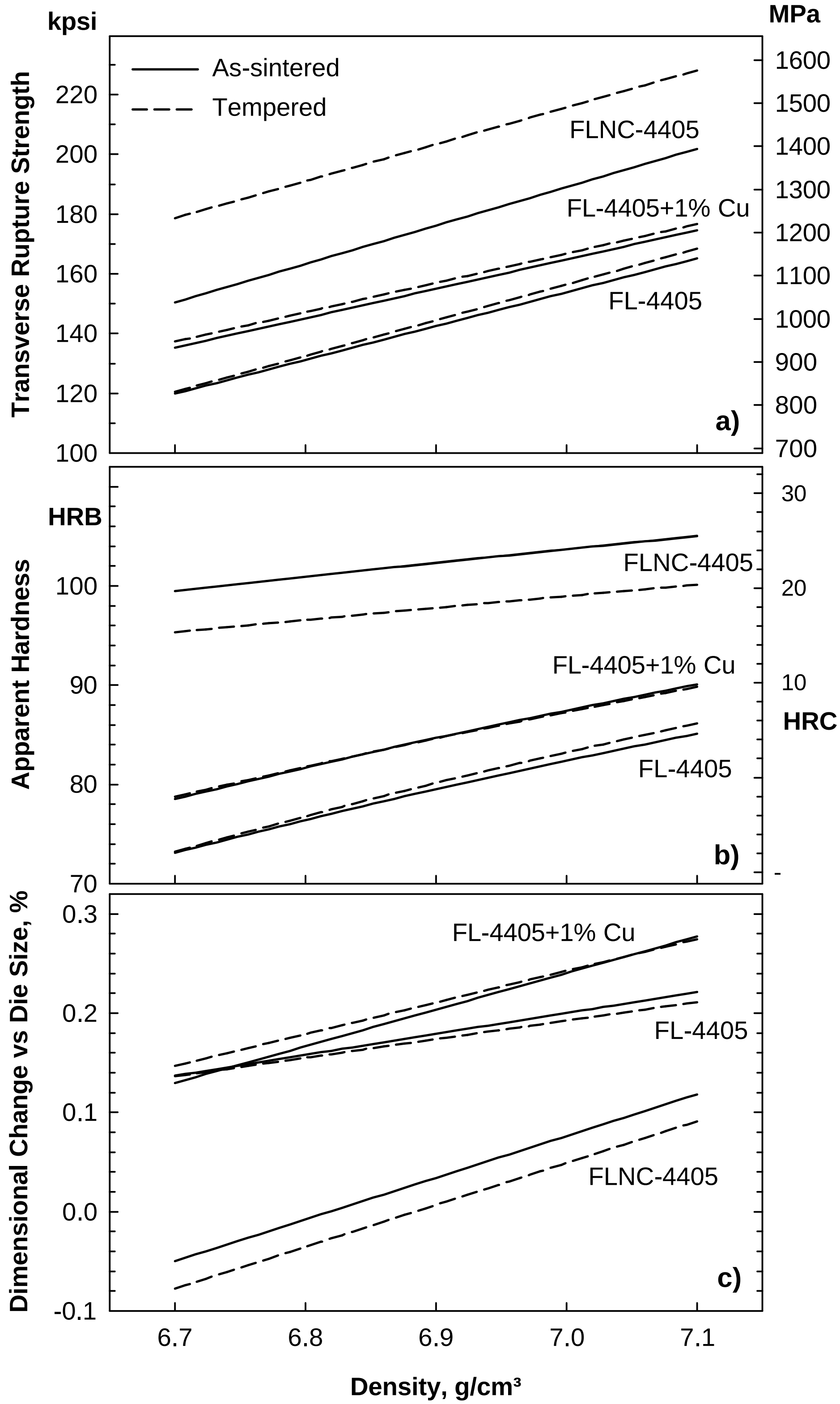


Figure 5. Effect of density on properties of FL-4405 (0.85% Mo pre-alloyed steel with 0.7% C), FL-4405 admixed with 1% Cu and FLNC-4405 (1% Cu-2% Ni) after sintering (1120°C/25 min) and after tempering (205°C/60 min): a) transverse rupture strength; b) apparent hardness and c) dimensional change from die size.

The effects of density on the TRS, apparent hardness and DC from die size of the three selected materials after sintering and after tempering are presented in Figure 5. These properties show a linear relationship with the density in the range investigated. Altogether, the three materials permit to obtain a large range of TRS and apparent hardness values: from 820 MPa and 72 $R_B$ for the FL-4405 base material at 6.7 g/cm³ up to 1590 MPa and 20 $R_C$ for the FLNC-4405 at 7.1 g/cm³. Typically, the raise in TRS for each increment of 0.1 g/cm³ in density varies from 70 MPa for the mix with 1% Cu to 90 MPa for the mix with 1% Cu-2% Ni. The apparent hardness increases at a rate of 5 to 10 Vickers for each increment of 0.1 g/cm³ in density. The tempering treatment at 205°C has no significant influence on the variation of TRS and apparent hardness with density. However, as already discussed, tempering is clearly beneficial for the TRS of the FLNC-4405 material (1% Cu-2% Ni) with an increase of about 200 MPa.

Regarding the DC versus die size, it becomes more positive with an increase of the density for all the materials, as usually observed. However, it is seen that the effect of density is larger for mixes containing copper with or without nickel. For instance, the variation in DC versus die size when density is raised from 6.7 to 7.1 g/cm³ is 0.09%, 0.15% and 0.17% for mixes containing no copper or nickel, 1% Cu and 1% Cu- 2% Ni respectively. The addition of 1% Cu to the FL-4405 material has no effect at low density but increases the DC by 0.07% at 7.1 g/cm³. The addition of 2% Ni to this latter material (FLNC-4405) decreases the DC by about 0.2% at all densities. It is worth mentioning that the effect of a tempering shows up for the Ni-containing mix only. It is also interesting to mention that if green size is considered instead of die size, the variation in DC is less important by about 0.09% when density increases from 6.7 to 7.1 g/cm³. This is explained by the fact that the green size of a part increases as the compacting pressure or density increases. Therefore, if DC versus green size is considered, there is no variation between 6.7 and 7.1 g/cm³ for the mix containing no copper or nickel and the variation is 0.06% and 0.08% for mixes containing 1% Cu and 1% Cu- 2% Ni respectively. This is illustrated in Figure 6 where the variation in DC versus green size when density increases from 6.7 to 7.1 g/cm³ as a function of the carbon content is shown for all the series of mixes evaluated in the paper. Typically, mixes without copper or nickel show no variation in DC when density is increased at any level of carbon content. With an addition of 1% or 2% Cu, the variation in DC due to a density change increases with the carbon content. The addition of 2% or 4% Ni further increases the trend.

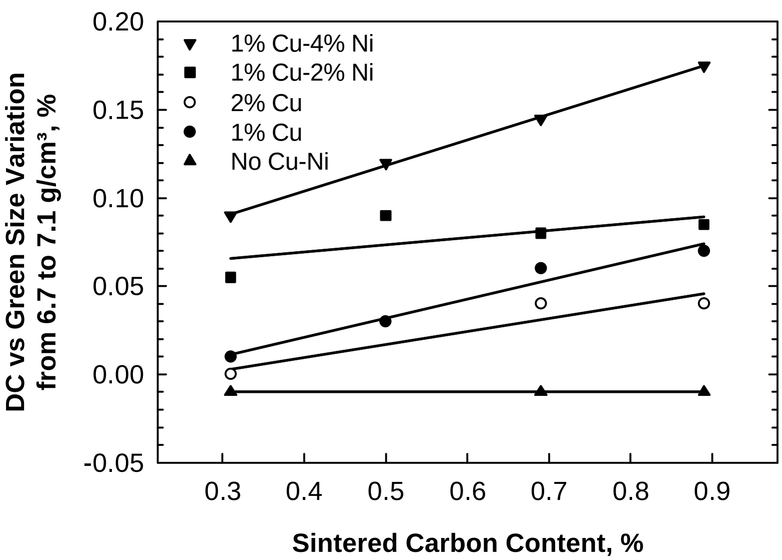


Figure 6. Variation in DC versus green size between 6.7 and 7.1 g/cm³ as a function of the carbon content for 0.85% Mo pre-alloyed steel powders admixed with different content of copper and nickel (after sintering and tempering).

The effects of density on the tensile properties of the three selected materials after sintering and after tempering are illustrated in Figure 7. The behavior of the UTS and YS is identical to that of the TRS: they increase quite linearly with the density. Tempering at 205°C has little effect on the base FL-4405 material without Cu or with 1% Cu but has a more significant effect on the FLNC-4405 material. Again a large range of UTS and YS can be achieved with these three materials: from 450 MPa in UTS and 370 MPa in YS for the FL-4405 base material at 6.7 g/cm³ up to 850 MPa in UTS and 600 MPa in YS for the

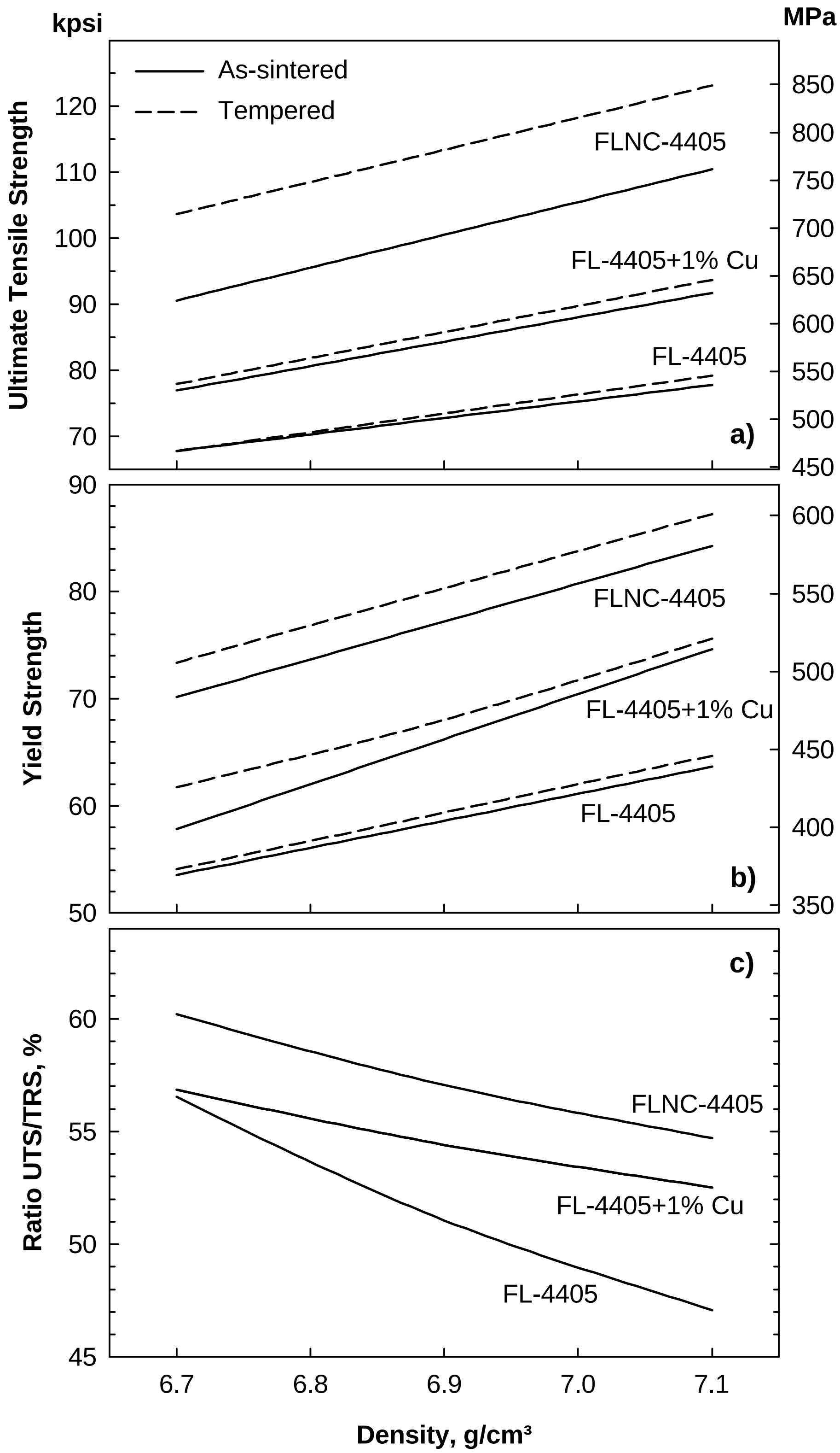


Figure 7. Effect of density on properties of FL-4405 (0.85% Mo pre-alloyed steel with 0.7% C), FL-4405 admixed with 1% Cu and FLNC-4405 (1% Cu-2% Ni) after sintering (1120°C/25 min) and after tempering (205°C/60 min): a) ultimate tensile strength; b) yield strength and c) UTS/TRS ratio.

FLNC-4405 material at 7.1 g/cm³. Depending on the material, the increase in UTS or YS varies between 17 and 34 MPa for each increment of 0.1 g/cm³ in density. The rate of increase in UTS and YS is more pronounced for mixes containing 1% Cu or 1% Cu and 2% Ni. Very similar rates of increase are achieved after tempering. Note that for the FLNC-4405 material, the tempering treatment has a much larger effect on the UTS than on the YS: an increase of 13% and 4% respectively.

TRS values are sometimes used to predict the ultimate tensile strength of P/M materials. Figure 7c shows the UTS/TRS ratio of the three selected materials as a function of the density. For all the materials, the ratio UTS/TRS decreases with the density, indicating that density has more effect on transversal resistance than on axial resistance. However, the decrease in UTS/TRS is less severe for the materials containing Cu or Cu-Ni. For instance, the UTS/TRS ratio decreases from about 57% at 6.7 g/cm³ for the mixes containing no Cu or 1% Cu down to 53% at 7.1 g/cm³ for the mix containing 1% Cu and 47% for the mix without copper.

***Effect of mix formulation and part thickness on dimensional stability.***

Several series of 5 rings 1.3 cm and 2.3 cm thick were pressed to 7.0 g/cm³ from ATOMET 4401 based mixes having a significantly different hardenability. The mixes described in Table II contained a total of either 3.15% or 5.5% graphite and metallic additives (1.25% Cu, 1.5% Ni and 0.4% C in the first case and 1.2% Cu, 3.5% Ni and 0.8% C in the second case). After compaction, rings were measured (2 diameters in top and bottom), sintered and tempered and the diameters measured again. Dimensional changes from green size were calculated from the mean diameters measured in the top and bottom of rings. The results are reported in Figure 8 for the 1.3 cm and 2.3 cm thick rings pressed from the low and high additive content mixes.

As expected, the DC decreases with an increase of the nickel and graphite content: from about -0.10% for the low additive content to -0.35% for the high additive content mix. The thickness of the rings has no significant effect on the DC at a level of 5.5% additives while it leads to a slight difference for the low additive mix: -0.14% for the 1.3 cm thick rings versus -0.08% for the 2.3 cm thick rings. This difference may be due to a lack of hardenability for the low additive mix combined with a change in cooling rate between the 1.3 and 2.3 cm thick rings. It is also seen that the DC at the top and bottom of the rings differs especially for the high additive content mix. This difference in DC between the top and the bottom of rings is considered as a measure of the distortion and is used to estimate the dimensional stability of mixes.

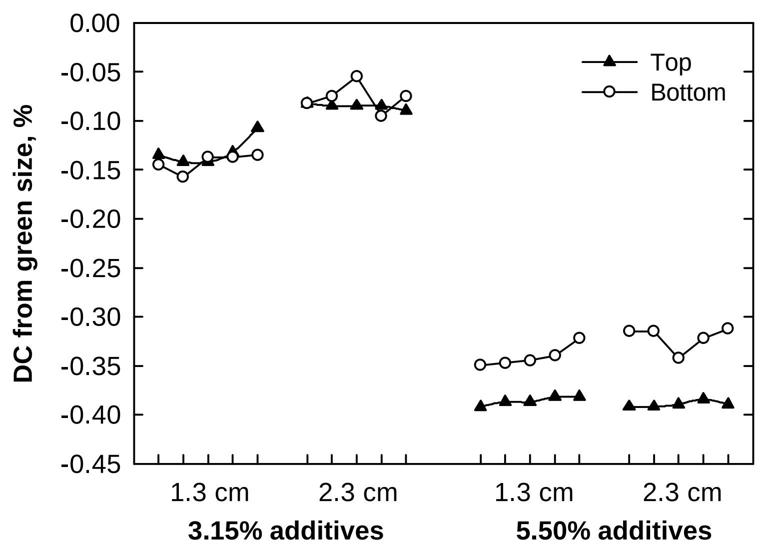


Figure 8. Dimensional change from green size calculated from the mean diameters measured at the top and bottom of rings (1.3 cm and 2.3 cm thick) pressed from ATOMET 4401 based mixes containing a total of either 3.15% or 5.5% of Cu, Ni and graphite additives.

The average absolute variation in DC (top versus bottom) with its standard deviation are reported in Figure 9 for the 1.3 cm and 2.3 cm thick rings pressed from the low and high additive content mixes. It appears that the quantity of additives in a mix has a significant impact on the dimensional stability of the parts. The distortion or DC variation between the top and the bottom of rings was about 0.01% for the mix containing 3.15% of Cu, Ni and graphite and about 5 to 6 times higher for the mix containing 5.50% of these additives. It is therefore clear that increasing the level of additives, and thus the hardenability, causes more distortion during sintering due to microstructural transformations. Furthermore, the distortion increases with an increase of the part weight or thickness when high levels of additives are used: from 0.045% for the 1.3 cm thick rings up to 0.068% for the 2.3 cm thick rings. Part thickness has no statistical influence on part distortion for the low additive mix. Considering this result and the fact that the DC of mixes with a low level of carbon are less sensitive to density variations, 0.85% Mo pre-alloyed steel powders admixed with 1% Cu , 2% Ni and 0.5% to 0.6% graphite are excellent candidate materials for applications requiring a very tight control of the DC. In addition, these mixes offer excellent compressibility, enabling high density and, as shown in this paper, very interesting mechanical properties.

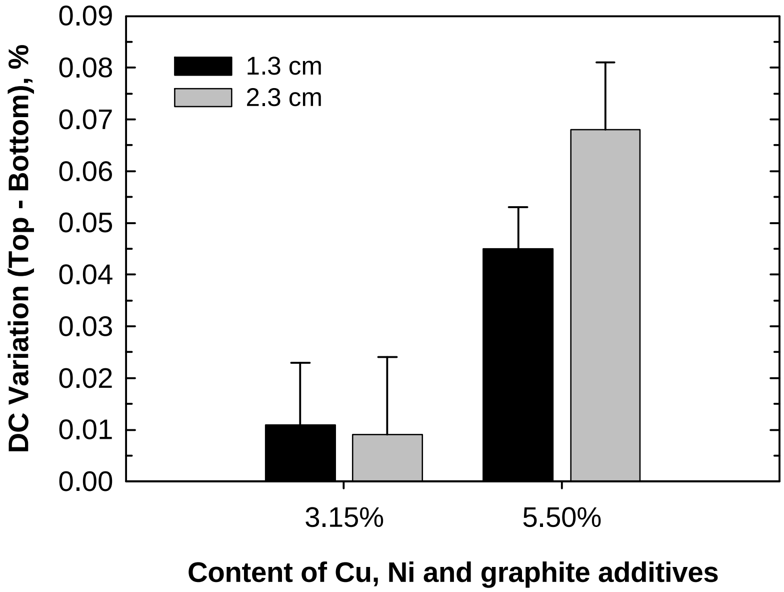


Figure 9. Difference in DC between the top and bottom diameters of rings (1.3 and 2.3 cm thick) pressed from ATOMET 4401 based mixes containing a total of either 3.15% or 5.5% of Cu, Ni and graphite additives.

## CONCLUSION

The effect of copper, graphite and nickel additives and density on the sintered properties of 0.85% Mo low alloy steel powders was studied as well as the dimensional stability of rings of different thicknesses made from mixes containing a low or high content in copper, graphite and nickel additives. The highlights of the study for this 0.85% Mo low alloy steel powder are:

- By adding 1% or 2% Cu and varying the carbon content from 0.3% up to 0.9%, TRS values between 895 MPa and 1340 MPa (130 kpsi and 195 kpsi) and apparent hardness between 72 $R_B$ and 100 $R_B$ are typically obtained at 6.9 g/cm³ after tempering. The DC from die size is almost independent of the carbon content at 1% Cu while it decreases almost linearly with an increase of the carbon content at 2% Cu. A tempering treatment at 205°C has little effect for the material containing 1% Cu and permits to recover TRS and UTS for the material containing 2% Cu.

- The addition of 2% or 4% Ni to the 0.85% Mo pre-alloyed powders admixed with 1% Cu and different levels of graphite further improves mechanical properties. For parts pressed to 6.9 g/cm³, TRS values between 1170 MPa and 1550 MPa (170 kpsi and 225 kpsi) and apparent hardness between 84 $R_B$ and 26 $R_C$ are typically obtained after tempering. The tempering treatment at 205°C has a beneficial impact on properties for carbon contents above 0.5%. At high carbon contents, these materials behave similarly to sinter hardened materials.

- The best overall static properties were achieved with an addition of 2% Ni and 1% Cu to the 0.85% Mo pre-alloyed powders: stable dimensional change with respect to the carbon content with an UTS of 850 MPa (123 kpsi) and YS of 600 MPa (87 kpsi) at 0.7% combined carbon and 7.1 g/cm³ in sintered density.

- The quantity of additives in a mix has a significant impact on the dimensional stability of parts: a DC variation between top and bottom of rings of about 0.01% and 0.05% were obtained for a mix containing a total of 3.15% and 5.50% of Cu, Ni and graphite additives respectively. It was also found that the part weight or thickness has a similar effect. For a mix containing 5.50% of Cu, Ni and graphite additives, a DC variation between top and bottom of rings of about 0.045% and 0.068% were obtained for 1.3 cm thick and 2.3 cm thick rings respectively.

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