



SELECTING LOW ALLOY MO STEEL POWDERS FOR HIGH PERFORMANCE
APPLICATIONS

by

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ABSTRACT

Many low alloy steel powder systems have been developed over the past several years to support the PM industry growth. These new powders were designed to reduce part manufacturing cost and improve mechanical properties. Pre-alloyed molybdenum was found to be effective in improving the hardenability of the base steel powder while maintaining a very good compressibility required to reach high sintered densities. A variety of alloys with 0.5%, 0.85% and 1.5% pre-alloyed Mo complemented with nickel and copper either diffusion-bonded, admixed or binder treated are now available to the P/M designers.

This paper presents a review of the physical and mechanical properties along with the compaction behavior of alloy systems based on steel powders with various levels of pre-alloyed Mo. This information may be used as a road map for the selection of alloy systems meeting specific requirements. This paper also includes a review of the dimensional stability, fatigue data and the typical microstructure of these systems.

INTRODUCTION

The number of high performance applications requiring sintered P/M components capable of withstanding severe operational stresses is continuously increasing. To attain the mechanical properties required for these demanding applications, the chemistry, microstructure, cleanliness and density must be optimized. In particular, it is well known that increasing the density is highly beneficial for the mechanical properties of PM parts, in particular the fatigue resistance [1,2,3]. Therefore, there is a strong need for highly compressible material having sufficient hardenability to reach the desired properties.

In recent years, numerous developments and improvements in steel powders considerably increased the density that can be reached as well as the attainable level of strength and fatigue resistance. In particular, a wide range of steel powder grades with different types and levels of

alloying elements either pre-alloyed into the melt prior to atomization or diffusion-bonded during the annealing treatment are commercially available to the market depending on the hardenability requirement. Amongst the alloying elements that can be added to steel powders, manganese, molybdenum and chromium are the most efficient for hardenability [4]. However, raising the concentration of alloying elements in steel powders usually leads to a deterioration of the powder compressibility [5]. In this sense, molybdenum is a very interesting alloying element since it only has a minor effect on powder compressibility. For these reasons, molybdenum low alloy steel powders are widely used to achieve high green density after compaction and high strength after sintering. Steel powders with various levels of molybdenum such as ATOMET 4001, 4401 and 4901 are available to the PM part producer. The physical and chemical characteristics of these molybdenum steel powders are given in Table 1.

In addition, elements such as nickel and copper can either be admixed or diffusion-bonded to these pre-alloyed Mo steel powders to further increase the hardenability and strength of P/M components while maintaining compressibility. Pre-alloyed molybdenum steel powders used with nickel, copper and graphite allow the formation of complex microstructures that are beneficial to the static and dynamic properties [6]. Mo-Cu-Ni-C formulations are widely used for highly stressed applications. A variety of diffusion-bonded powders are available in the market such as ATOMET DB46, DB48 and DB49. The chemistry and physical properties of these powders are given in Table 1. In addition, the binder-treatment technology can be used to attach the nickel, copper and graphite to the steel particles during the blending operation and to produce formulations identical to the diffusion-bonded powder grades. The binder-treatment consists of adding an organic binder to the pre-mix during the blending operation that bonds the metallic, graphite and other additives to the steel particles, therefore strongly reducing the segregation and dusting of these elements during handling. Also, the flow characteristics of the powder mixes are significantly improved, resulting in better die cavity fill and a more stable part-to part weight. The production rate can also be increased in some cases without affecting part quality and integrity.

Table 1. Physical and chemical characteristics of molybdenum steel powders

	Regular grades			Diffusion-bonded grade		
	AT4001	AT4401	AT4901	DB46	DB48	DB49
<i>App. Dens., g/cm³</i>	2.92	2.92	3.00	3.02	3.02	3.05
<i>Flow, s/50g</i>	27	26	25	24	24	23
<i>-325 mesh, %</i>	21	25	28	24	24	22
<i>+100 mesh, %</i>	12	10	10	10	10	7
<i>Carbon, %</i>	0.002	0.002	0.002	0.002	0.002	0.002
<i>O, %</i>	0.08	0.08	0.09	0.08	0.08	0.09
<i>Mo, %¹</i>	0.5	0.85	1.5	0.5	0.5	1.5
<i>Mn, %¹</i>	0.15	0.15	0.15	0.15	0.15	0.15
<i>Ni, %²</i>	-	-	-	1.75	4.0	4.0
<i>Cu, %²</i>	-	-	-	1.5	1.5	2.0

1. Pre-alloyed to the steel powder
2. Diffusion-bonded during annealing

This paper presents a review of the green and mechanical properties of alloy systems based on steel powders with various levels of pre-alloyed Mo. The influence of Ni, Cu and/or graphite is also presented. Particular attention is paid to the dimensional stability of Mo steel powders.

I. COMPRESSIBILITY OF MOLYBDENUM STEEL POWDERS

As discussed earlier, molybdenum is a good alloying element to increase the hardness and strength of P/M steels without strongly affecting the compressibility. This is better illustrated in Figure 1, which shows the influence of the molybdenum content on the green density achieved at 600 MPa for a mix formulation of molybdenum powder-0.8% graphite-0.75% Zt St. It is seen that increasing the molybdenum content up to 0.85% has only a minor effect on compressibility while a further increase induces a slight drop in compressibility. However, a density in excess of 7.00 g/cm³ can still be achieved at 600 MPa or 43.5 tsi with a steel powder containing 1.5% molybdenum.

The compressibility is not only influenced by the base steel powder but also by the mix formulation. Figure 2 shows the effect of graphite content on the compressibility of a 0.85% molybdenum steel powder. At relatively low density and compacting pressure, the level of graphite has little effect on green density. However, when compacting pressure is increased, the density decreases as the level of graphite increases. For instance, at 60 tsi, increasing the level of graphite from 0.4 to 1.0% results in a reduction in density of about 0.15 g/cm³. This must be considered when high density is targeted.

Amongst the additives added to the mix, the internal lubricant has the most significant effect on compressibility. Due to its very low specific gravity (about 8 times lower than steel), internal lubricant significantly reduces the achievable maximum density. For this reason, the level of lubricant must be maintained as low as possible when density of 7.2 g/cm³ or higher is targeted. However, reducing the lubricant content requires the use of very efficient lubricant to minimize friction at die walls. Such a lubricant system is used in warm pressing materials. The die wall lubrication technique can also be used to reduce the level of internal lubricant and further

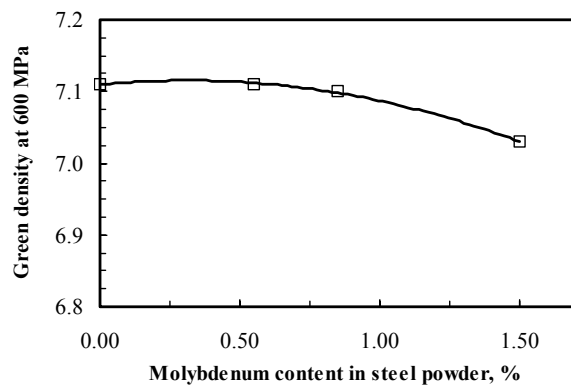


Figure 1. Effect of molybdenum content on the compressibility.

Mix: Mo steel powder + 0.8% graphite + 0.75% Zn

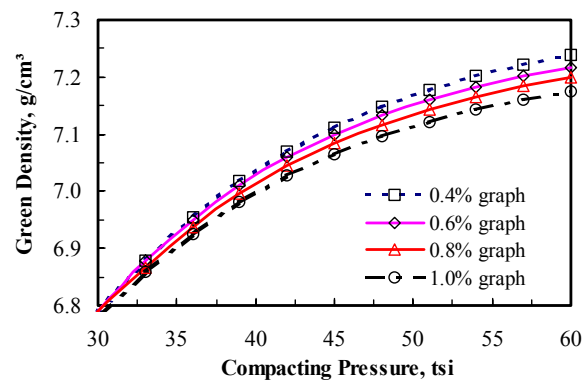


Figure 2. Effect of the graphite content on the compressibility curves of powder mixes made of ATOMET 4401+ 1%Cu + graphite + 0.75% Zn St

increase the green density. Figure 3 shows the compressibility curves of 0.85% molybdenum powder mixes compacted by cold pressing, warm pressing and die wall lubrication. Densities in the range of 7.30 to 7.45 g/cm³ can be achieved when compacting pressures in the range of 50 to 60 tsi are applied with warm compaction and die wall lubrication. The green density is limited to a maximum of 7.24 g/cm³ with a regular mix containing 0.75% wax.

Nickel and copper powders are also commonly added to molybdenum steel powders to increase the strength and hardness. They can be either admixed with or without binder treatment or diffusion-bonded. Whatever the type of product selected by the part producer, the compressibility remains very similar as shown in Figure 4.

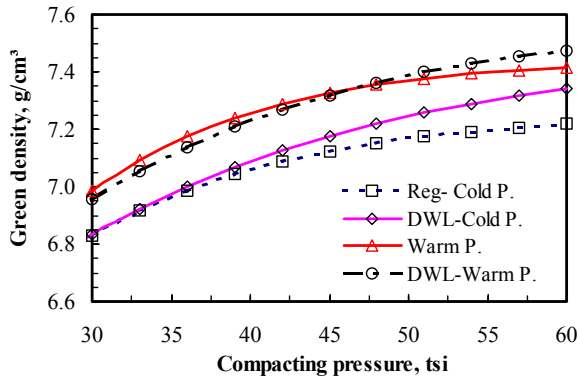


Figure 3. Compressibility curves of Mo steel powder mixes pressed with different compacting methods. Mix: ATOMET 4401-1.5Cu-4Ni-0.6 grap+ lub

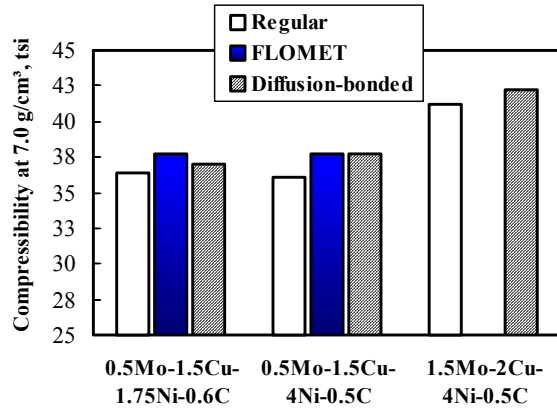


Figure 4. Compressibility of regular, binder-treated and diffusion-bonded molybdenum steel powders at 7.0 g/cm³

II. MECHANICAL PROPERTIES

The static properties of molybdenum steel powders admixed either with graphite, copper and/or nickel are discussed in the following section. Properties are given at a sintered density of 7.0 g/cm³. In all cases, specimens were sintered at 1120°C (2050°F) for 25 min in a nitrogen atmosphere containing 10% hydrogen. The cooling rate between 650 and 400°C (1200-750°F) was about 0.65°C/sec (1.17°F/s) except when specified. Some properties are also given after tempering for 1 hr in air at 205°C (400°F).

a. As-sintered properties

Effect of molybdenum content

Figure 5 shows the influence of the molybdenum content in steel powder on the apparent hardness, tensile and yield strength for various powder mix formulations containing 0.5% carbon. It should be noted that similar trend is obtained at other levels of sintered carbon. In all cases, increasing the molybdenum content leads to an increase in strength and apparent hardness. The effect is more pronounced between 0.5 and 0.85% molybdenum. Indeed, the hardness and

strength tends to level off when molybdenum content reaches a concentration of 1 to 1.2%. Figure 6 shows the typical microstructure of molybdenum steel powders admixed with 1.5% copper, 4% nickel and 0.6% graphite (sintered carbon \approx 0.5%). The microstructure of such formulations is heterogeneous with areas of divorced pearlite, fine pearlite/bainite, martensite and Ni-rich retained austenite. The microstructure within steel particles where nickel did not diffuse changed gradually from divorced pearlite/pearlite/bainite to bainite/martensite as the amount of molybdenum increased. This change is more evident between 0.5 and 0.85% molybdenum. Indeed, the shift in microstructure is less pronounced between 0.85 and 1.5% molybdenum. These transformations in microstructure explain the variation in mechanical properties previously discussed and presented in Figure 5.

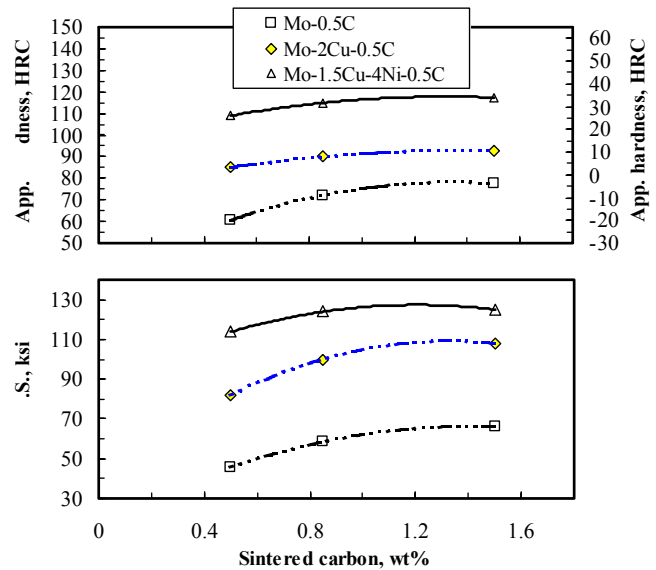


Figure 5. Influence of Mo content on apparent hardness and strength for various powder mix formulation.

Effect of carbon and copper content

Figure 7 shows the influence of carbon on the apparent hardness and strength of powder mixes made with 0.85 and 1.5% molybdenum steel powder and admixed either with 1 or 2% copper. The apparent hardness increases linearly with the sintered carbon content for both levels of copper. It should be noted that an identical trend is achieved without adding copper. Increasing the Mo content in the steel powder also contributed to a slight change in apparent hardness.

For materials containing 1% copper, the strength follows a similar trend as the apparent hardness, i.e. it increases with the carbon content. The strength and hardness are both optimized at \sim 0.9% carbon with 1% copper. No significant difference in strength is observed between the 0.85% to 1.5% molybdenum powders. A different trend is observed for molybdenum powders containing 2% copper. Indeed, it is seen that the strength is maximized for a carbon content of \sim 0.7% for both 0.85 and 1.5% molybdenum. Above this point, the strength is reduced with an increase of the level of carbon. The reduction in the as-sintered strength when carbon content exceeds 0.7% for molybdenum steel powders admixed with 2% copper is linked to the formation of significant proportion of martensite.

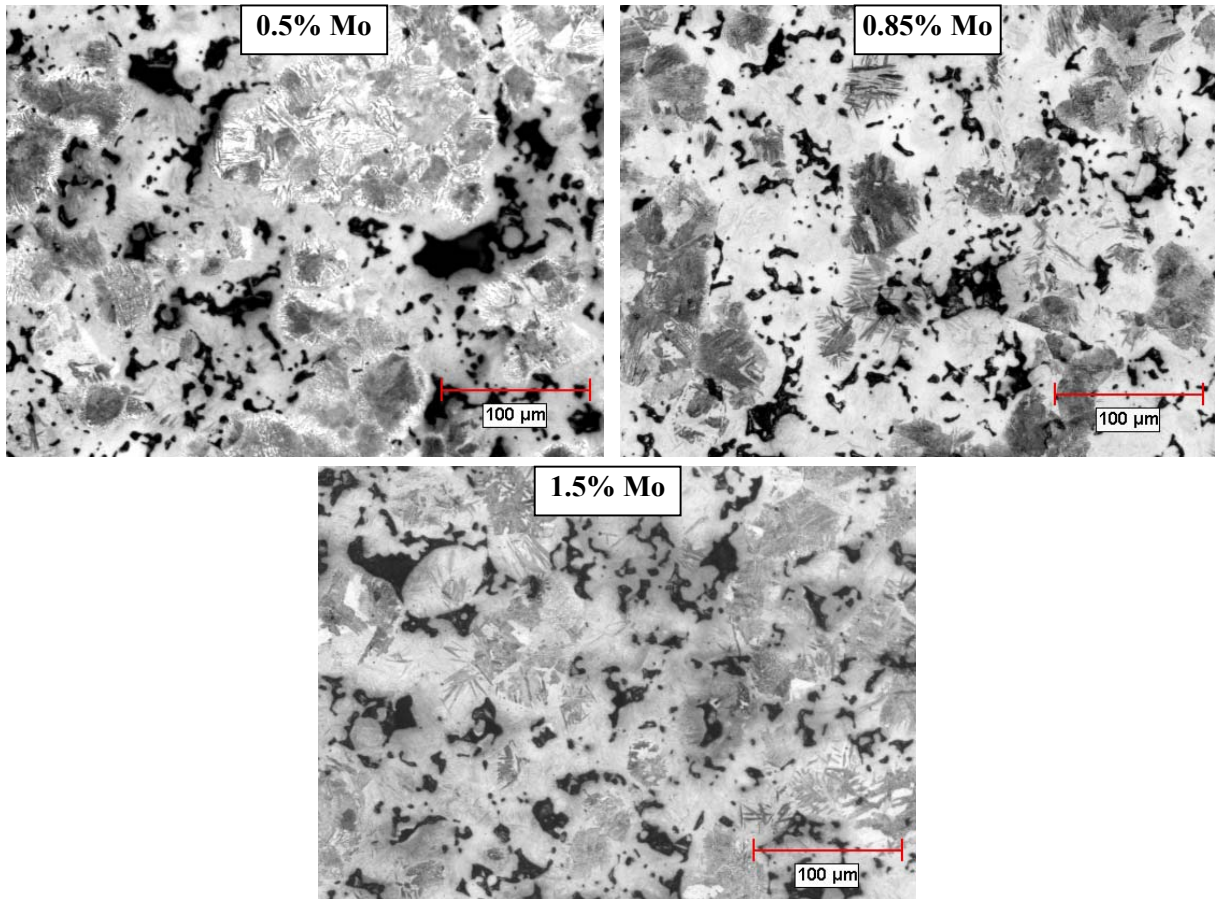


Figure 6. Typical microstructures of regular mixes made with 0.5, 0.85 and 1.5% Mo steel powders admixed with 4%Ni, 1.5%Cu and 0.6% graphite. (Specimens pressed to 7.0 g/cm³).

Effect of carbon, nickel and copper

Figure 8 shows the apparent hardness and sintered strength as a function of the sintered carbon content for molybdenum steel powders admixed with 4% nickel and 1% copper. Curves obtained with 1% copper without nickel addition are also given as reference. As it was the case for the copper-carbon system, increasing the level of carbon lead to an increase in apparent hardness, which tends to level off at about 0.7% carbon for materials containing 4% nickel. As compared to the powder mixes with 1% copper, the addition of 4% nickel induces a significant increase in apparent hardness at any level of sintered carbon.

The addition of nickel also strongly influences the strength. Indeed, for low carbon content, the strength is significantly improved by adding 4% nickel. In fact, the strength is maximized for a carbon content of ~ 0.5% with 4% Ni. Above this point, the strength decreases with the carbon content. The optimum level of carbon moved from 0.9% at 1% copper to 0.7% at 2% copper and 0.5% at 1% copper-4% nickel. In fact, the higher the hardenability, the lower the optimum carbon content in the as-sintered state. It is worth mentioning that using a steel powder with 1.5% molybdenum instead of 0.85% contributed to an increase in strength for carbon content

lower than 0.5%. For example, at 0.3% sintered carbon, the strength is increased by 25 ksi by increasing the molybdenum content from 0.85 to 1.5%.

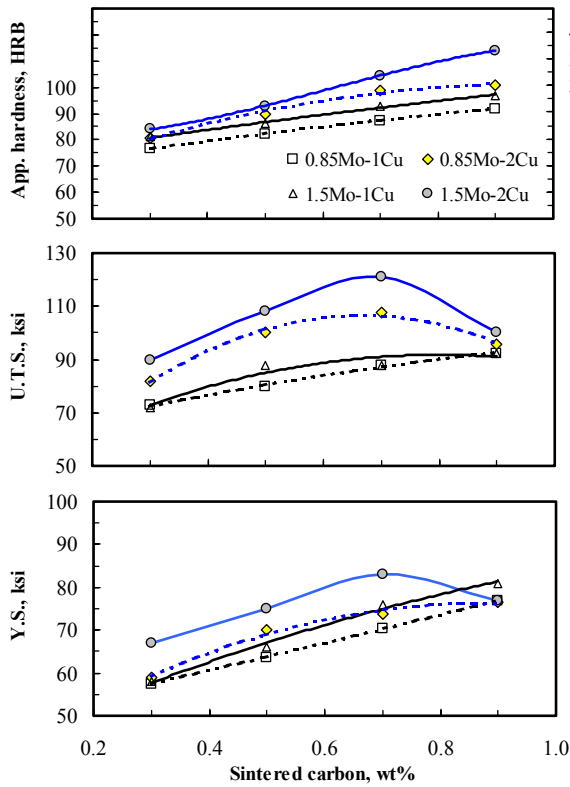


Figure 7. Influence of carbon content on the sintered properties of Mo steel powders admixed with graphite and Cu at 7.0 g/cm³.

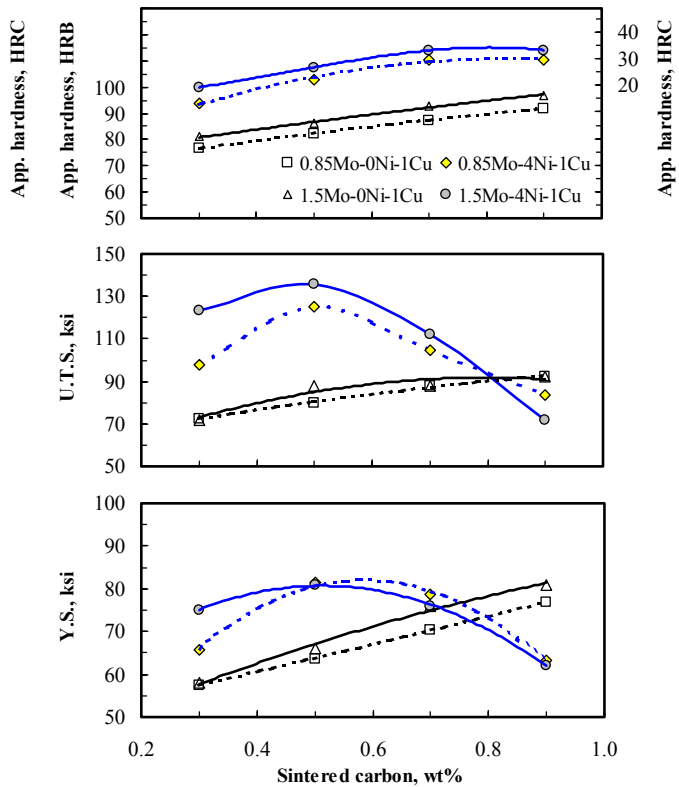


Figure 8. Influence of carbon content on the sintered properties of Mo steel powders admixed with graphite, Cu and 0 and 4% Ni at 7.0 g/cm³.

Figure 9 shows the influence of sintered carbon and copper content on the sintered properties of 1.5% molybdenum steel powder admixed with 4% nickel. Increasing the copper content from 0 to 1% led to a slight increase in apparent hardness at low carbon content. A further increase in copper content from 1 to 2% does not change the apparent hardness. In all cases, the apparent hardness tends to level off when carbon content is increased. Increasing the copper content from 0 to 1% leads to a slight improvement in strength for carbon content lower than 0.7%. However, the carbon content maximizing the strength remains at ~ 0.4 to 0.5% for both formulations. A further increase in copper content from 1 to 2% moves the optimum carbon content from 0.5 to ~ 0.3-0.35%.

b. Influence of tempering

It is well known that for hard structures, performing a tempering treatment on parts significantly improves the strength with only a slight reduction in apparent hardness. On the other hand, tempering has little or no effect on sintered properties for soft material. Figure 10 shows the relation between the apparent hardness in the as-sintered state and strength before and after

tempering at a density of 7.0 g/cm^3 for molybdenum steel powders admixed with various additives. The apparent hardness is given in Knoop hardness number (Khn) in order to include the hardness values in both the Rockwell B and C scales. It can be seen that tempering starts to be effective when apparent hardness exceeds about 225 Khn, which is equivalent to about 96 HRB or 15 HRC. Of course, the hardness at which tempering starts to be effective increases with density. For instance, it is about 90 HRB at 6.8 g/cm^3 and 98 HRB or 18 HRC at 7.2 g/cm^3 .

It can also be seen in Figure 10 that there is large scattering in tensile strength, especially in the as-sintered state, when hardness values exceed about 225 KHN. This indicates that hardness is not the only factor contributing to the strength. In fact, this large scattering is strongly related to the level of sintered carbon in parts as shown in Figure 11a. For hardness values exceeding 225 KHN, it can be seen that increasing the level of carbon in the part reduces the strength for a given hardness level. This clearly indicates that to optimize both the hardness and strength in the as-sintered state, it is highly beneficial to use carbon content of $\sim 0.5\%$ and increase the hardenability by adding sufficient amount of nickel and/or copper. More precisely, the formulation maximizing both the strength and hardness in the as-sintered steel powders was a 0.85 or 1.5% molybdenum steel powder with 4% nickel, $\sim 1\%$ copper and $\sim 0.5\%$ carbon. The properties of such formulations were $\sim 28 \text{ HRC}$ in hardness, $\sim 130 \text{ ksi}$ in tensile strength and $\sim 80 \text{ ksi}$ in yield strength at 7.0 g/cm^3 .

If tempering is performed, the level of carbon has less influence on the strength as shown in Figure 11b. This is mainly due to a significant improvement in strength due to the tempering for carbon content of 0.7% or higher as shown in Figure 12. For carbon content of 0.5% or less, tempering has no beneficial effect on tensile strength but reduces the hardness if the as-sintered hardness is above 220 KHN or 95 HRB. The reduction in apparent hardness associated with

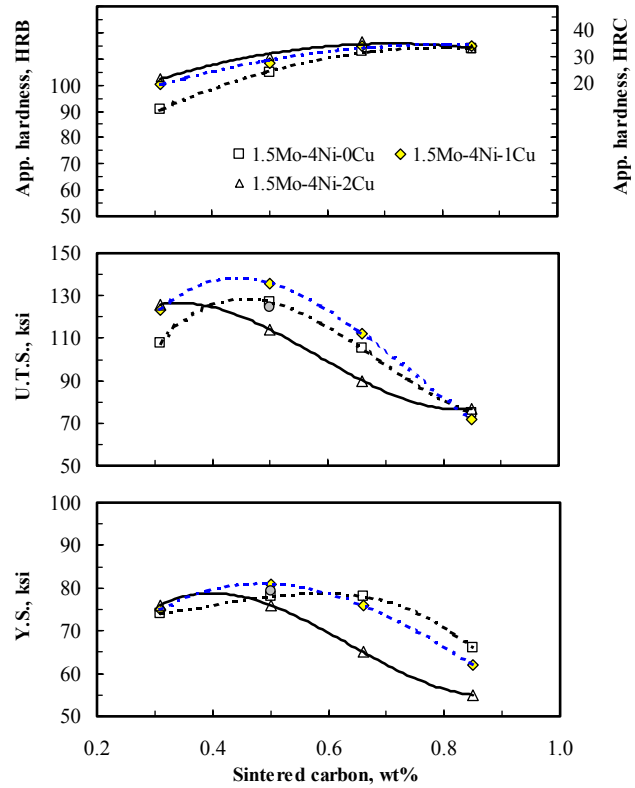


Figure 9. Influence of carbon content on the sintered properties of 1.5% Mo steel powders admixed with graphite, Ni and 0, 1 and 2% Cu at 7.0 g/cm^3 .

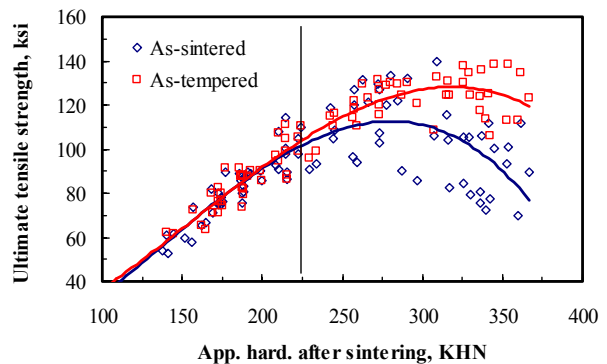


Figure 10. Influence of the apparent hardness before tempering on the tensile strength before and after tempering for Mo steel powders at 7.0 g/cm^3 .

tempering increased with the as-sintered hardness. On the other hand, the level of carbon has no significant effect on the variation in hardness during tempering.

The formulations maximizing both the strength and hardness after tempering are as follows:

- 1.5% molybdenum powder with 2% copper and 0.9% carbon
- 1.5% molybdenum powder with 4% nickel, 1% copper and 0.7% carbon
- 0.85% molybdenum powder with 4% nickel, ~ 1% copper and 0.7 to 0.9% carbon.

The properties of such formulations were as follows: 25-30 HRC, 130-140 ksi in tensile strength and 80-90 in yield strength.

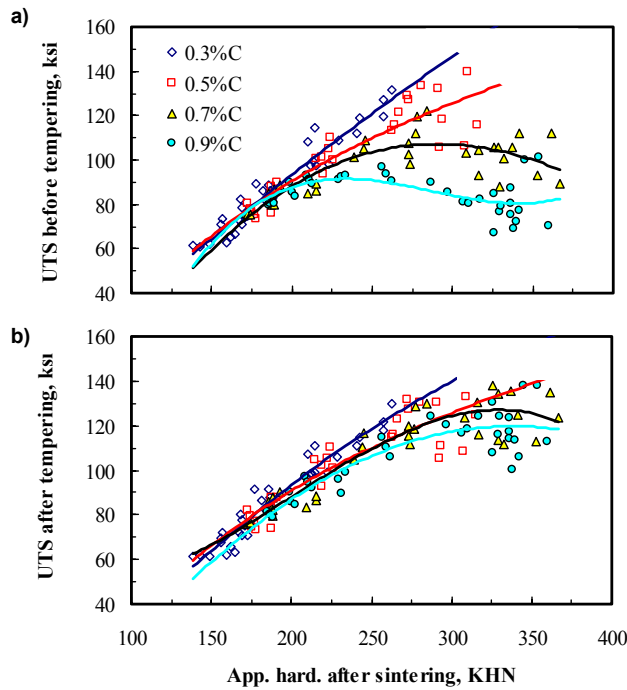


Figure 11. Effect of apparent hardness and carbon content on tensile strength (a) before tempering (b) after a tempering.

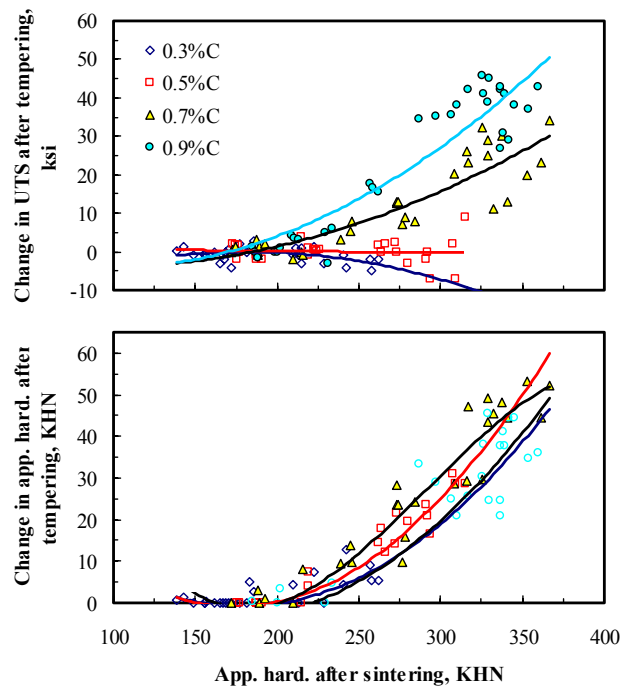


Figure 12. Influence of apparent hardness and carbon content on tensile strength and apparent hardness of tempered Mo steel materials.

c. Effect of density on mechanical properties

It is well known that increasing the density, and thus reducing the amount and size of pores in the PM part increases the apparent hardness and strength. Figure 13 illustrates the effect of green density on the mechanical properties after tempering of powder mixes made with a 0.85% molybdenum powder admixed with 1.5% copper, 4% nickel and 0.6% graphite (final sintered carbon of ~ 0.5%) and various levels of lubricant and pressed by cold pressing (CP), warm pressing (WP), cold die wall lubrication pressing (DWL-CP) and DWL combined with warm pressing (DWL-WP). The compressibility curves of these materials are given in Figure 3.

As expected, hardness and strength increase with density. However, it can be seen that the strength tends to level off with the reference material pressed by cold compaction. This can be explained by the high level of internal lubricant in the mix, which limits the densification and likely reduces the quality of inter-particle bonding achieved after sintering. Reducing the level of internal lubricant combined with the use of an effective compacting method is therefore beneficial not only for the achievable density but also for the mechanical properties through better inter-particle bonding.

d. Effect of cooling rate on the mechanical properties of 1.5% Mo steel powder

Sinter-hardening is defined as a process where martensitic transformation occurs during the cooling stage of the sintering [7]. To achieve high apparent hardness after sintering, the base powder must have sufficient hardenability. Proper additions of metallic additives and graphite further increase the hardenability. In addition, the cooling rate in the sintering furnace must be sufficiently high to promote martensitic transformation. Sintering furnaces are now equipped with fast cooling units that allows reaching high cooling rates between 650 and 400°C (1200-750°F). The 1.5% molybdenum powder admixed with proper levels of additives is a good candidate for sinter-hardening applications.

Figure 14 shows the influence of sintered carbon and cooling rate on the apparent hardness and strength of 1.5% molybdenum steel powder admixed with 1 or 2% copper in both the as-sintered and as-tempered states at 7.0 g/cm³. Increasing the carbon content caused an increase in apparent hardness. Also, increasing the cooling rate contributes to increase the apparent hardness at 1 and 2% copper. Apparent hardness in the range of 40 to 50 HRC in the as-sintered state and 35 to 40 HRC after tempering is achieved with a cooling rate of 1.85°C/s (3.33°F/s) and carbon content between 0.7 and 0.9%C. No significant difference in apparent hardness is observed between 1 and 2% copper for sintered carbon of 0.7% or higher.

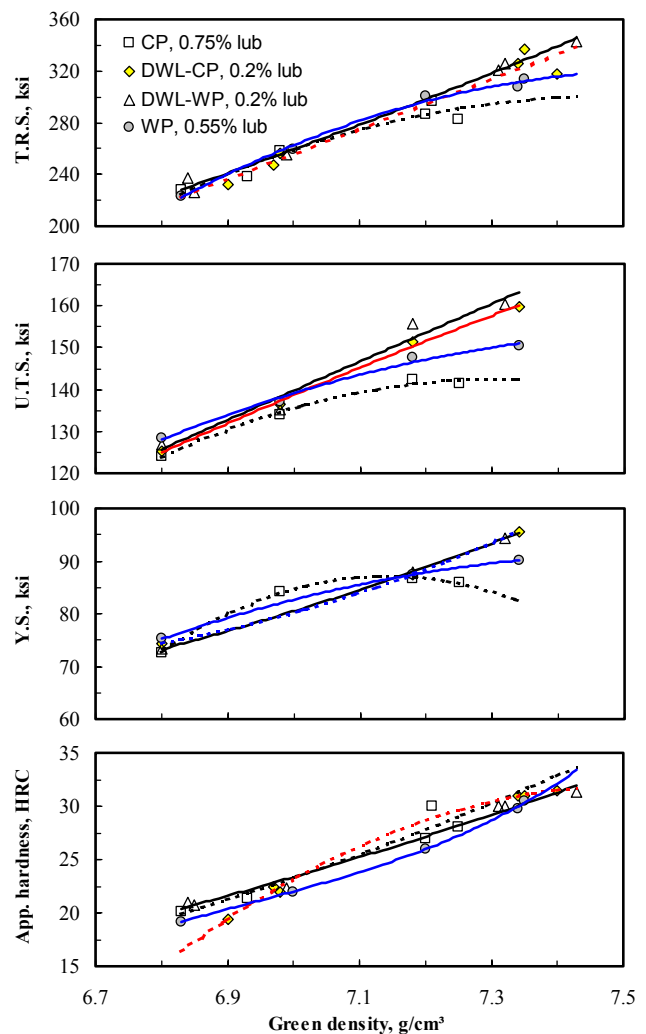


Figure 13. Effect of green density on strength and apparent hardness after tempering 0.85%Mo powder mixes compacted by different processes. Mix: Mo powder - 4Ni-1.5Cu-0.5C-lube.

No significant difference in tensile strength is observed when increasing the cooling rate from 0.65 to 1.85°C/sec for carbon content of 0.6% or lower in the as-sintered state. However, the combination of tempering and a cooling rate of 1.85°C/s (3.33 °F/s) between 650 and 400°C (1200-750°F) is beneficial for tensile strength. This property reaches about 150 ksi at 0.7% carbon and 2% copper. However, using a fast cooling rate and tempering did not result in a significant change in tensile strength for 1% copper. Finally, using a faster cooling rate results in a significant improvement in yield strength, especially after tempering and for carbon content of 0.7% or lower. The yield strength reaches about 90 ksi with 2% copper and 0.7% carbon.

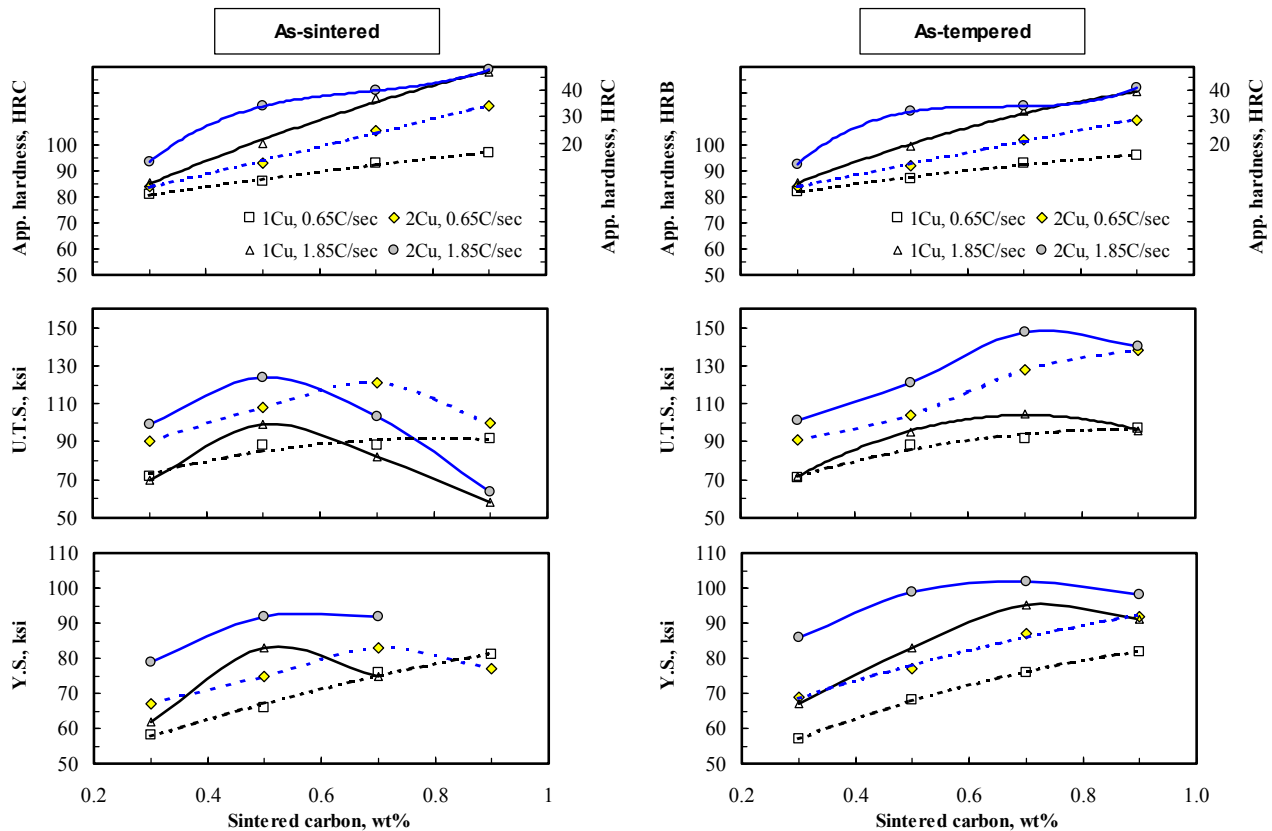


Figure 14. Effect of sintered carbon content and cooling rate between 650 and 400 °C on the mechanical properties of 1.5% molybdenum steel powders admixed with copper.

III. DIMENSIONAL STABILITY

The dimensional change that occurs during sintering is a key characteristic to take into account when producing parts, especially when parts with high apparent hardness and/or density are produced. Indeed, machining of materials showing high hardness can be very difficult. In addition, machining is an additional step in parts manufacturing that increase the overall production cost.

To obtain consistent part dimensions, the sintering conditions, typically the delubing, the maximum temperature, the time at this temperature and the cooling rate must be well controlled.

In addition to that, several other factors must be considered such as the dimensional stability of the base powder, the additives, the formulation, the density and the density gradient.

Figure 15 shows the influence of molybdenum content on the dimensional change after sintering at a density of 7.0 g/cm³ for various mix formulations. In general, increasing the molybdenum content gives slightly more negative dimensional change, the differences in dimensional change between 0.5 and 1.5% molybdenum being of the order of -0.05%.

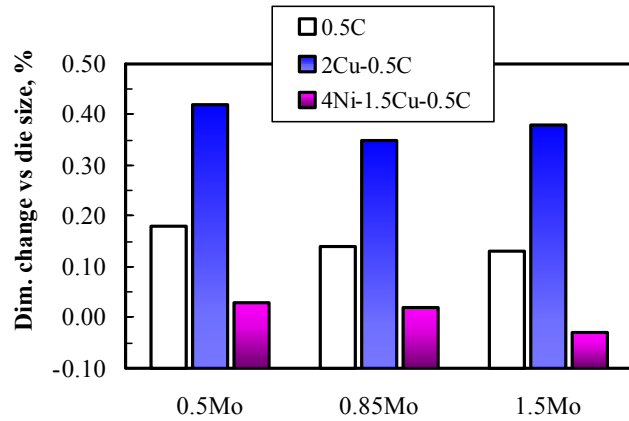


Figure 15. Dimensional change of ATOMET 4401 at 7.0 g/cm³ for various powder mix formulations.

Figure 16 shows the influence of sintered carbon on the dimensional change after sintering of a 0.85% molybdenum powder containing copper (fig 16a) and nickel (fig 16b). Similar trends are obtained with steel powder containing 0.5 and 1.5% molybdenum. At 0% copper, the dimensional change becomes more positive with carbon content while at 1% copper, the dimensional change remains constant with carbon content. At 2% copper, the opposite trend is observed, the dimensional change decreasing with the carbon content. It can be seen that higher variation in dimensional change is observed at 2% copper, especially at low carbon content. The segregation and carbon dusting that may occur during handling of the powder mix may cause important part-to-part dimensional change variation. However, at 1% copper, excellent stability in dimensional change is achieved.

It can be seen in Figure 16b that adding nickel to a mix containing 1% copper shifts the dimensional change towards more negative values, the shift being proportional to the amount of nickel added. At 2% nickel and 1% copper, the dimensional change remained constant when carbon content is increased. However, at 4% nickel and 1% copper, the dimensional change decreased with an increase of carbon content, the variation being about -0.14% between 0.3 and 0.9% carbon.

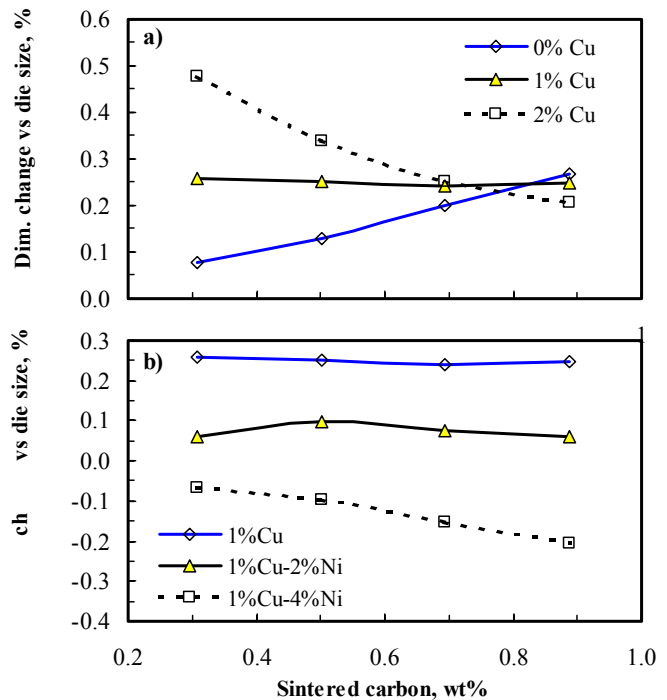


Figure 16. Influence of carbon, copper and nickel content on the dimensional change of mixes made with a 0.85%Mo steel powder at 7.0 g/cm³.

Tempering performed on parts having high hardness induces a variation in dimensional change that varies from -0.03 to -0.10% for a cooling rate of 0.65°C/s (1.17°F/s). The material showing a larger variation in dimensional change after tempering is the 1.5% molybdenum powder admixed with 2% copper and 4% nickel. The tempering performed on parts that were cooled between 650 and 400 °C (1200-750°F) at a rate of 1.85°C/s (3.33°F/s) induced a more important shift in dimensional change. This can be explained by the higher proportion of martensite formed when using a faster cooling rate. Indeed, it was shown by a previous study on sinter-hardening steel powders that the variation in dimensional change during tempering was related to the proportion of martensite and the level of carbon in the specimens [8]. The shrinkage obtained during tempering is due to the transformation of martensite from a tetragonal body-centered structure to a hexagonal structure [9].

CONCLUSIONS

A review of the compressibility, mechanical properties and dimensional stability of steel powders containing either 0.5, 0.85 or 1.5% molybdenum and admixed with graphite, copper and/or nickel was presented. The key characteristics of the molybdenum steel powder are as follows:

- Molybdenum steel powders show very good compressibility. Indeed, densities close to 7.10 g/cm³ can be reached at 43.5 tsi or 600 MPa.
- Densities in the range of 7.30 to 7.45 g/cm³ can be reached with a 0.85% molybdenum powder admixed with 4% nickel, 1.5% copper and 0.6% graphite and compacted with pressures ranging between 50 and 60 tsi (690 and 830 MPa) by warm compaction and die wall lubrication combined or not with warm compaction.
- As a result of these high densities, ultimate tensile strength and yield strength in excess of 160 and 90 ksi are attainable with this formulation in the as-tempered state.
- Increasing the molybdenum content from 0.5 to 1.5% increases the apparent hardness and strength, the effect being more pronounced between 0.5 and 0.85% molybdenum.
- For 0.5, 0.85 and 1.5% molybdenum powders admixed with graphite and 0 or 1% copper, the optimum level of sintered carbon maximizing both the strength and hardness in the as-sintered state is about 0.9%.
- For molybdenum powders admixed either with 2% copper or 2 to 4% nickel with or without copper, the optimum level of carbon maximizing the as-sintered strength and hardness is shifted toward lower concentration. It is about 0.7% carbon for molybdenum-2% copper formulations and 0.5 to 0.6% carbon for molybdenum-1% copper-4% nickel formulations.
- To maximize both the strength and hardness in the as-sintered state, it is recommended to use a 0.85 or 1.5% molybdenum steel powder and maintain the level of sintered carbon at 0.5% or lower and add nickel and copper to raise hardenability. Tensile strength of 130 ksi, yield strength of 90 ksi and apparent hardness of 28HRC can be achieved at 7.0 g/cm³.
- Tempering may improve the strength with a slight reduction in hardness when the as-

sintered apparent hardness is in excess of 95 to 100 HRB. The effect of tempering on mechanical properties is a function of the hardness and level of carbon.

- For carbon content of 0.5% or lower, tempering has little or no effect on strength even at high hardness values. However, for carbon content of 0.7% or higher, tempering is highly beneficial to the strength, the gains in tensile strength increasing generally with the initial as-sintered hardness and the level of carbon.
- The optimum formulation to maximize both the strength and hardness after tempering is either a 1.5% molybdenum powder admixed with 2% copper and 0.7 to 0.9% carbon or 0.85 or 1.5% molybdenum powder with 4% nickel, 1 to 1.5% copper and 0.7 to 0.9% carbon. Tensile strength up to 140 ksi, yield strength up to 90 ksi and apparent hardness varying from 25 to 30 HRC can be achieved at 7.0 g/cm³.
- The 1.5% molybdenum powder can exhibit good sinter hardening characteristics if a fast post-sintering cooling rate and effective formulation are used. Indeed, increasing the cooling rate from 0.65 to 1.85°C/s (1.17 to 3.33°F/s) between 650 and 400°C (1200-750°F) significantly improved the hardness, reaching up to 48 HRC with 1 and 2% copper at 7.0 g/cm³. Tensile strength of ~150 ksi, yield strength of ~100 ksi and apparent hardness of 35 HRC can be achieved with 2% copper and 0.7% carbon after tempering at 7.0 g/cm³.
- The powder mix formulation has a great influence on the dimensional change value and stability. To optimize dimensional change robustness, the recommended level of copper is about 1%.

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