



The Development and Characteristics of Low Alloy Steel Powders for Sinterhardening Applications

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ABSTRACT

Sinterhardening is an attractive technique for the manufacture of high hardness P/M parts since it eliminates the need for post sintering heat treatment, thus significantly reducing processing costs. Furthermore, high thermal stresses and part distortion resulting from conventional quenching are avoided, providing improved control on final part dimensions.

To achieve a homogeneous microstructure throughout the sintered part, it is preferable to add alloying elements such as nickel, manganese, chromium and molybdenum in the melt prior to atomization. In contrast, mixtures of elemental powders will result in a heterogeneous microstructure with inferior properties. A new low alloy steel powder, ATOMET 4701, was specifically designed to promote sinterhardening of P/M parts in industrial sintering furnaces equipped with either conventional or rapid cooling units.

A production size batch of this new low alloy steel powder was characterized with additions of graphite and copper, ranging from 0.6 to 1.0% and 0 to 2% respectively. Apparent hardness and tensile properties were evaluated after sintering at 2050°F (1120°C) using a cooling rate of 1.3°F/s (0.7°C/s) and also after tempering for one hour at 400°F (205°C). The highest apparent hardness was achieved for a mix containing 1% graphite and 2% copper in the as-sintered condition. Optimum tensile properties were obtained after tempering, for a mix containing 0.8% graphite and 2% copper.

INTRODUCTION

Sinterhardening can be defined as a process where P/M parts transform partially or completely into a martensitic structure during the cooling phase of the sintering cycle. In order to achieve optimum hardenability, prealloying techniques are generally preferred to elemental additions. Manganese is added to all commercial steels in the range of 0.25 to 1.0% to increase strength and hardenability of plain carbon steels. Chromium is also a very popular element for improving hardenability, strength and wear resistance of conventional steels. However, in P/M steels, manganese and chromium contents are generally maintained below 0.3% because of the difficulty to reduce their oxides during annealing [1]. Molybdenum and nickel are

commonly used in low alloy P/M steel powders because their oxides are easily reduced during the annealing treatment of water atomized powders. Molybdenum is very efficient for increasing the strength and hardenability of steels while nickel increases the hardenability, strength, toughness and fatigue resistance [2]. These elements are however more expensive than manganese or chromium and are subject to large market price variations.

Figure 1 illustrates the effect of molybdenum, manganese, nickel and chromium concentrations on the hardenability multiplying factor [3]. Manganese has the most pronounced effect on hardenability followed by molybdenum, chromium and nickel. However, since molybdenum and nickel are expensive alloying elements, it was decided to partially substitute these with manganese and chromium.

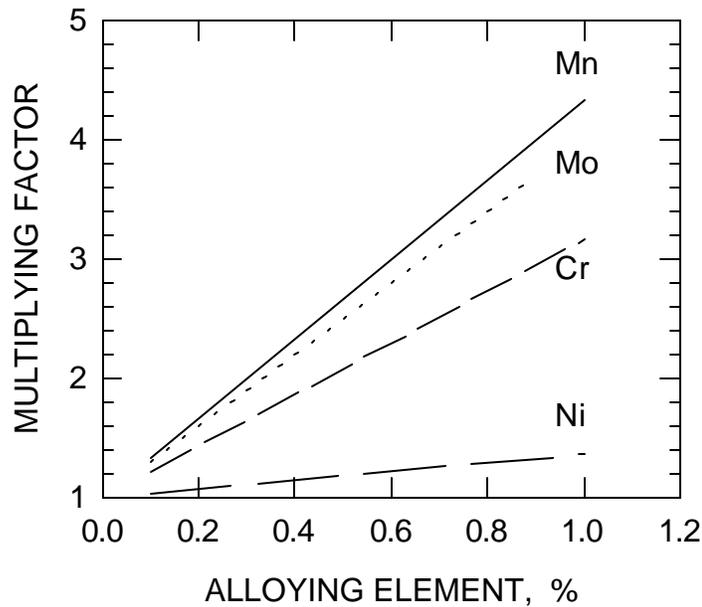


Figure 1. Hardenability multiplying factor of manganese, molybdenum, chromium and nickel [3].

An R&D program was carried out to develop a new prealloy steel powder with improved hardenability to promote sinterhardening in conventional sintering furnaces. In order to reduce the development time and the production scale-up of this new powder grade, the program was initiated using the Advanced Product Quality Planning principles[4]. The specific objective of the program was to develop a steel powder capable of achieving a minimum apparent hardness of 30 HRC after sintering in a conventional furnace, while maintaining powder compressibility above 6.8 g/cm³ at 40 tsi (550 MPa). The first part of the program was the development of the alloy composition on a laboratory scale. Results of this study have been presented previously [5]. It is worth noting that low alloy steel powders used for sinterhardening applications must show good hardenability in order to transform austenite into martensite even at low cooling rates. This phase transformation is controlled both by the cooling efficiency of the sintering furnace and the load on the belt (small or large parts). As illustrated in Figure 2, the apparent hardness decreases with specimen weight but the effect is more pronounced for the powder that has a lower hardenability. This is related to the microstructure; as the weight increases, compacts made with the lower hardenability powder show a significant drop in martensite content.

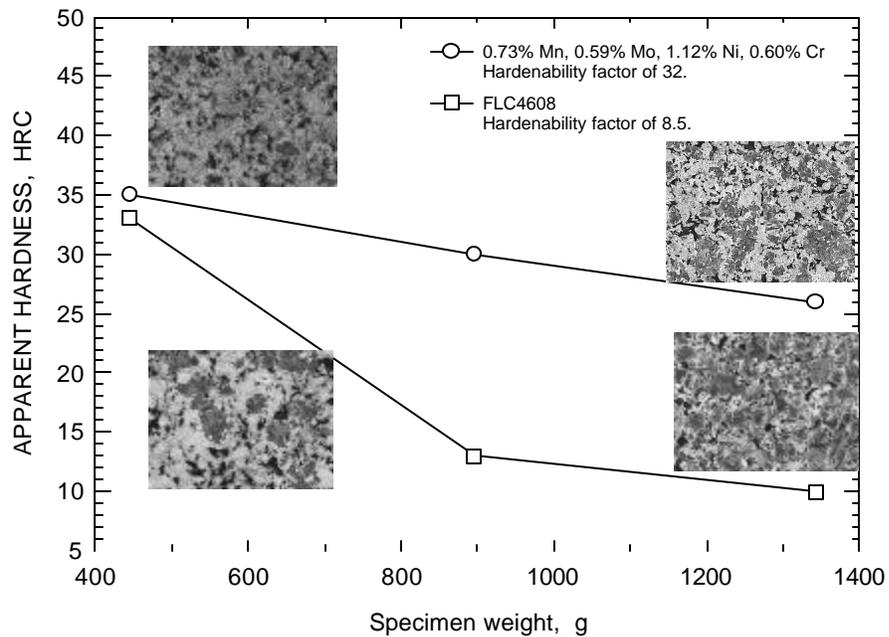


Figure 2 Effect of weight on the surface hardness of specimens made from low and high hardenability powders. [Ref. 5]

EXPERIMENTAL PROCEDURE

After optimization of the alloy chemistry on a laboratory scale, QMP proceeded with the production of this new sinterhardening grade, ATOMET 4701. This is a water atomized and fully prealloyed steel powder specifically designed for sinterhardening applications. Table 1 shows the physical and chemical properties of ATOMET 4701.

TABLE 1
Physical and Chemical Properties of ATOMET 4701

Apparent Density g/cm ³	Flow s/50g	C %	O %	S %	Cr %	Mn %	Mo %	Ni %	Fe %	Hardenability factor
2.92	26	0.01	0.25	0.009	0.45	0.45	1.00	0.90	Bal.	26.5

The sintered properties of production grade powder were determined using test mix compositions with 0, 1% and 2% copper along with graphite additions of 0.6 to 1.0%. All mix formulations contained 0.75% Zinc Stearate. Test specimens were pressed to 6.8 g/cm³ and sintered 30 minutes at 2050°F (1120°C) in dissociated ammonia. Sintering was done in a conventional belt furnace having a cooling rate of 1.3°F/s (0.7°C/s) from 1600 to 1200°F (870 to 650°C). After sintering, the test pieces were tempered for one hour in air at 400°F (205°C). Tensile properties were determined using round machined specimens according to MPIF standard 10.

RESULTS AND DISCUSSION

Sintered properties for the various mix formulations are given in Table 2.

TABLE 2
Sintered properties of specimens made from ATOMET 4701 and various additions of copper and graphite.

Graphite %	Copper %	As-sintered			After tempering		
		UTS, kpsi (MPa)	YS, kpsi (MPa)	App. Hard. HRC	UTS, kpsi (MPa)	YS, kpsi (MPa)	App. Hard. HRC
0.6	2.0	92 (635)	75 (515)	16	98 (680)	88 (610)	16
0.7	2.0	112 (770)	87 (600)	25	105 (725)	89 (610)	21
0.8	2.0	86 (590)	83 (570)	30	111 (765)	93 (640)	25
0.9	2.0	75 (515)	75 (515)	33	120 (825)	89 (610)	26
1.0	2.0	69 (475)	69 (475)	34	109 (755)	80 (550)	27
0.9	1.0	82 (565)	80 (550)	22	101 (695)	83 (575)	23
0.9	0	76 (520)	66 (455)	6	77 (535)	65 (445)	5

Apparent Hardness

Apparent hardness measurements in the as-sintered and tempered conditions are reported in Figures 3 and 4. Figure 3 shows the hardness as a function of carbon content for a mix containing 2% Cu. In the as-sintered state, hardness increases with carbon, both as a consequence of the solution hardening effect of carbon as well as the progressively increasing amount of martensite in the structure. At the moderate cooling rate of 1.3°F/s (0.7°C/s) used in these tests, a maximum amount of martensite and hence hardness is reached at 0.85% sintered carbon. Tempering decreases the hardness, relative to the as-sintered condition, by progressively larger increments as the carbon level and in turn the proportion of martensite increases. However, as will be subsequently shown, tempering significantly improves the strength of the sinterhardened structure.

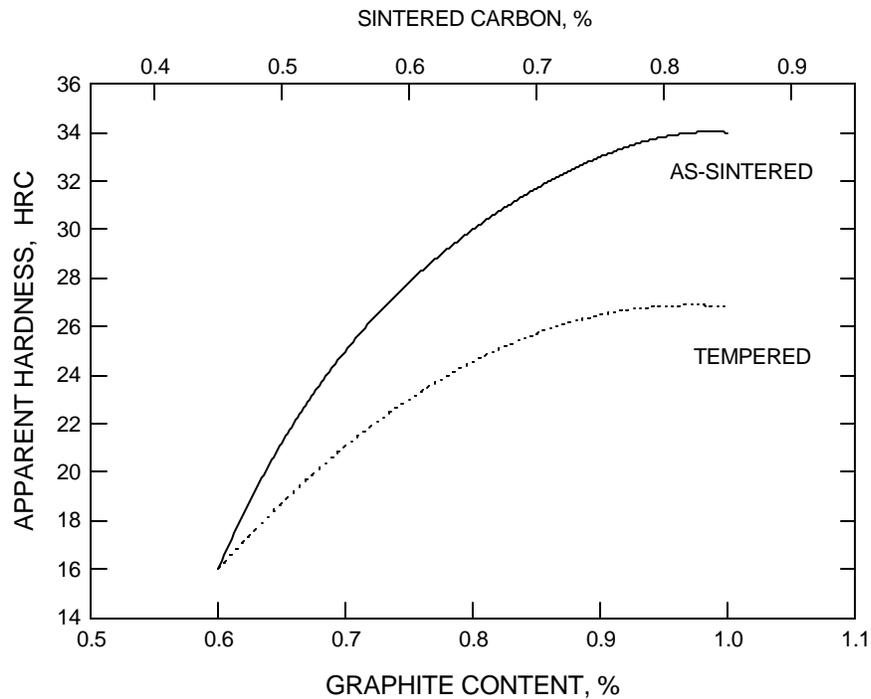


Figure 3. Effect of graphite content on apparent hardness after sintering and after tempering. (Mix containing 2% copper)

Figure 4 shows the hardness as a function of the copper addition in the range of 0 to 2.0%, for a constant graphite level of 0.9% (or 0.75% sintered carbon). Copper increases the hardenability of the material, which starts to form an appreciable amount of martensite above the 1% Cu level. Therefore, the decrease in tempered hardness is only evident above 1% Cu and is in direct relation to the amount of martensite formed during the cooling cycle. It is interesting to note that a given hardness value, i.e. 25 HRC, could be attained by either adjusting the cooling/tempering conditions of a mix containing 2% Cu or alternatively by reducing the copper level in the blend and avoiding the tempering stage. The latter option would certainly be more cost effective.

Tensile Properties

The ultimate tensile strength for the various mix formulations is shown in Figures 5 and 6. Figure 5 presents the UTS as a function of sintered carbon or graphite content for the same formulations discussed in the previous section. In the as-sintered condition, the tensile strength increases to a maximum of 112 kpsi (770 MPa) at about 0.5% sintered carbon. This is caused by the initial strengthening effect of carbon in a mixed structure composed of pearlite, bainite and martensite. However as the relative proportion of the brittle martensite phase increases, the tensile strength rapidly declines and levels out as the structure reaches its maximum martensite content at about 0.8% sintered carbon. Tempering increases the strength to a maximum of 120 kpsi (825 MPa) at 0.7% sintered carbon, which coincides with the eutectoid composition of this formulation. The formation of brittle carbides at higher carbon levels causes a reduction in strength.

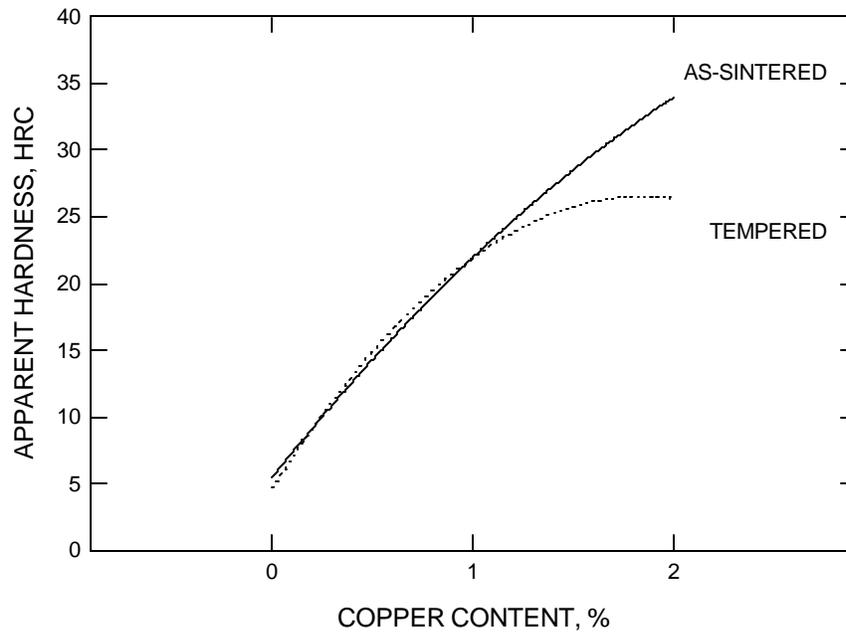


Figure 4. Effect of copper content on apparent hardness after sintering and after tempering. (Mix containing 0.9% graphite)

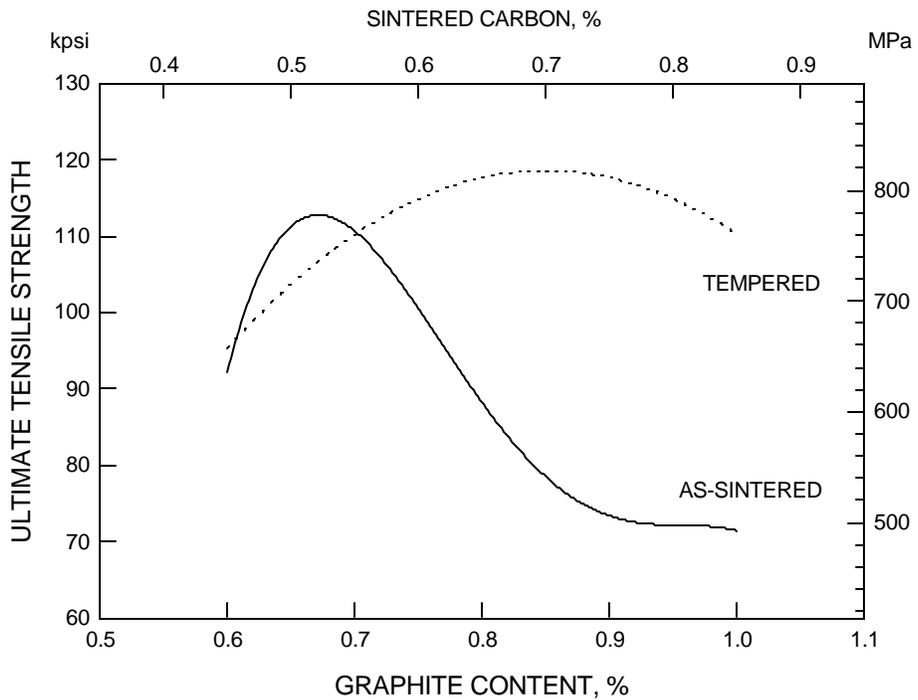


Figure 5. Effect of graphite content on ultimate tensile strength after sintering and after tempering. (Mix containing 2% copper)

Figure 6 shows the UTS as a function of copper content for a fixed addition of 0.9% graphite (0.75% sintered carbon). The as-sintered tensile strength is not significantly affected by the copper level under these test conditions. The strengthening effect of the copper is being nullified by the progressively increasing amount of brittle martensite in the structure as copper content increases. In contrast, after tempering, UTS increases linearly with the copper level. This reflects the larger amount of martensite formed as the copper increases.

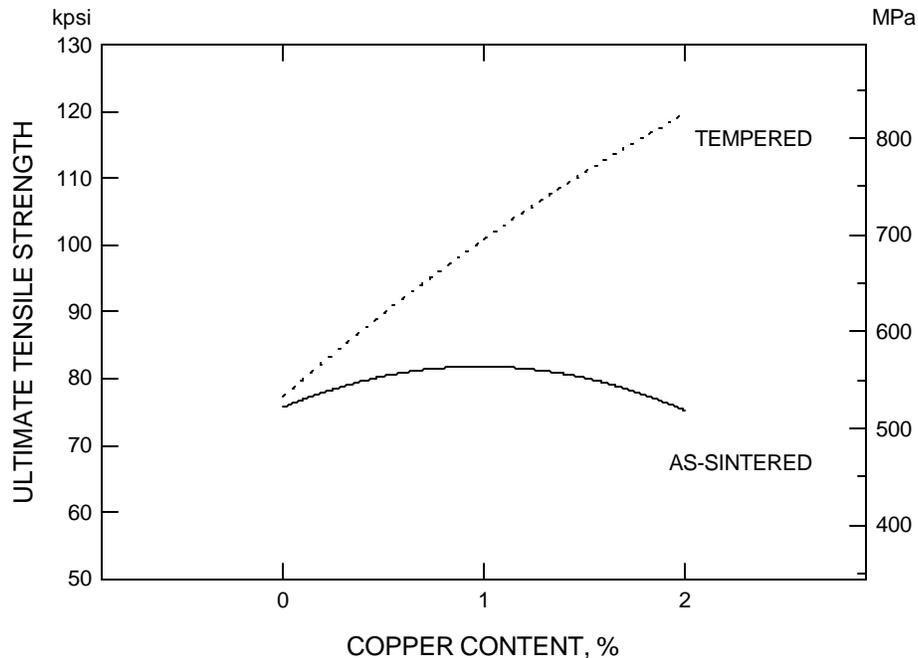


Figure 6. Effect of copper content on ultimate tensile strength after sintering and after tempering. (Mix containing 0.9% graphite)

The effect of carbon and copper content on yield strength is shown in Figures 7 and 8. Not surprisingly, these hardened structures are characterized by low elongation (< 1%). Since the martensite/bainite content is around 70% above 0.7% combined carbon, the untempered materials do not exhibit a significant yield point. Therefore at the higher carbon levels, ultimate tensile and yield strengths of the as-sintered specimens are comparable. In Figure 7, the general trend for tempered yield strength as a function of carbon content is similar to that of the ultimate tensile strength. A maximum of 93 kpsi (640 MPa) is reached at about 0.65% sintered carbon and 2% Cu. Figure 8 shows that the tempered yield strength, at a constant 0.9% graphite level, increases with copper additions. The untempered specimens achieve a maximum yield strength at about 1% copper. It subsequently declines due to the increased formation of untempered martensite.

Figure 9 illustrates the evolution of martensite content in relation to the graphite and copper levels. The specimen microstructures are shown in Figure 10. Raising the copper content enhances the hardenability and consequently promotes the formation of martensite. Specimens with a carbon content of 0.75% C (or 0.9% admixed graphite) without copper show a low quantity of martensite, about 5%. The microstructure is mainly composed of very fine pearlite. An addition of 1% copper increases the martensite content to 50%. For a 2% copper addition, increasing the carbon content from 0.45% to 0.85%, graphite addition of 0.6 to 1%, raises the martensite level from 70 to 80%.

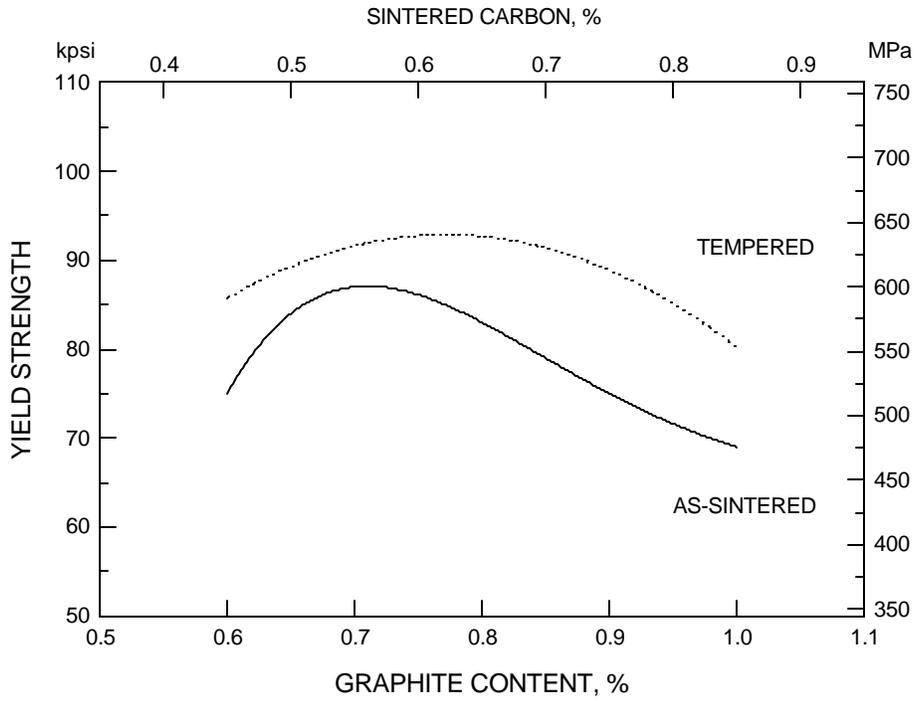


Figure 7. Effect of graphite content on yield strength after sintering and after tempering. (Mix containing 2% copper)

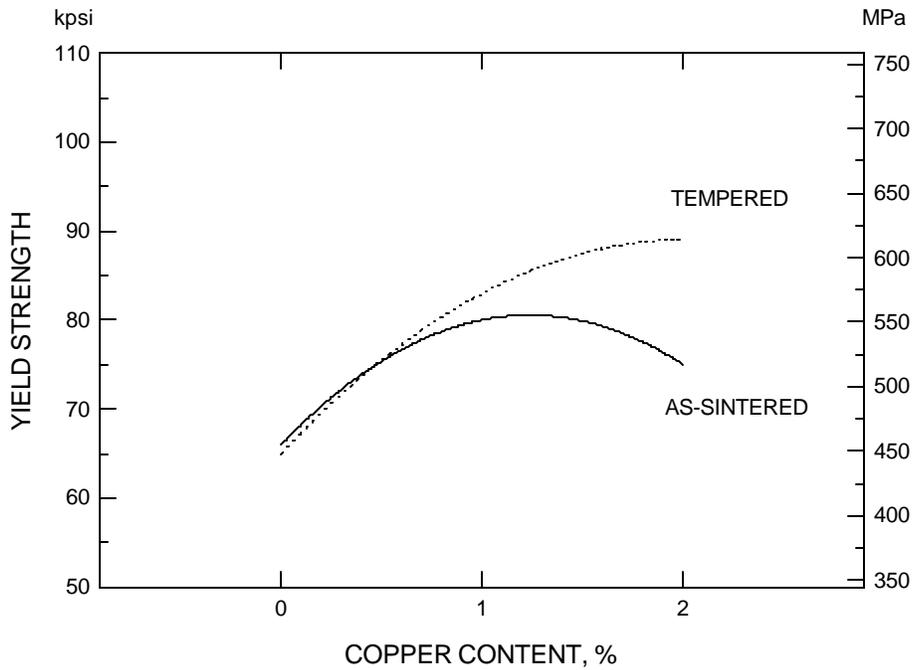


Figure 8. Effect of copper content on yield strength after sintering and after tempering. (Mix containing 0.9% graphite)

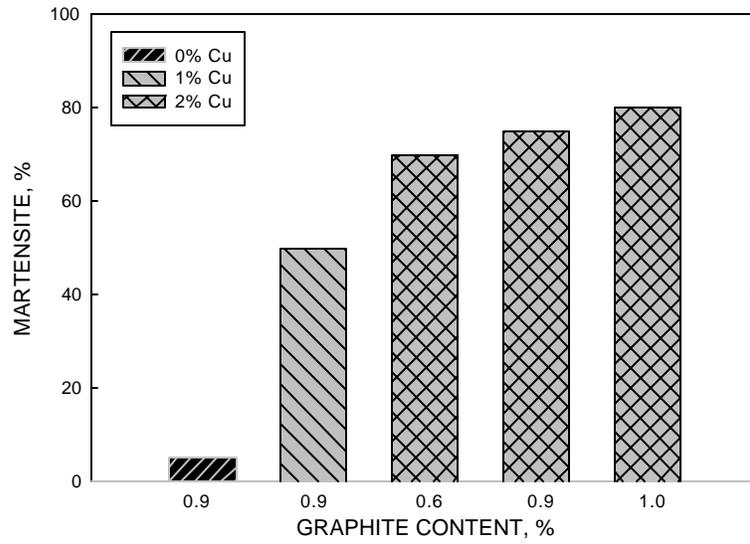


Figure 9. Effect of admixed graphite and copper levels on the martensite content.

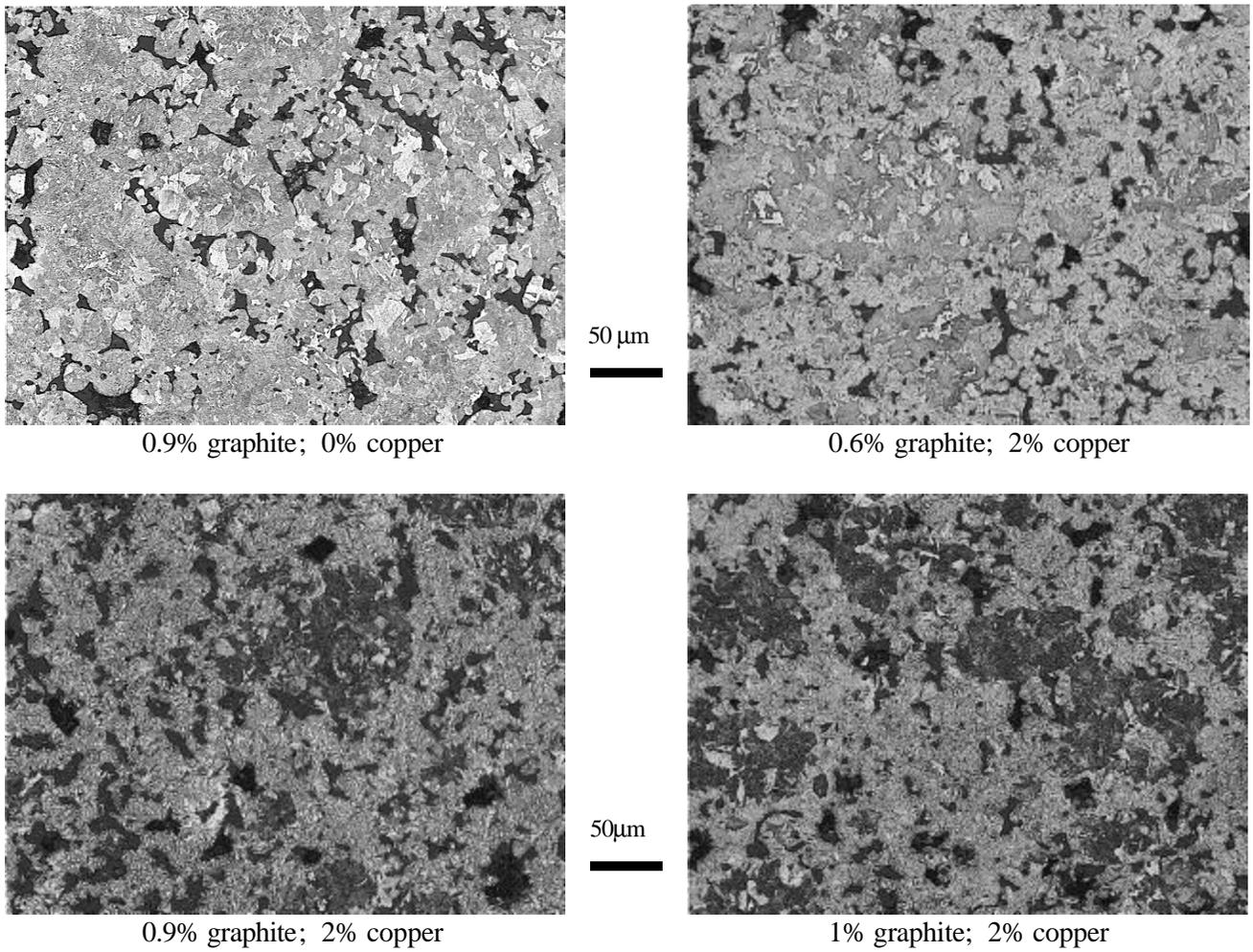


Figure 10. Microstructure of test specimens containing various amounts of graphite and copper.

CONCLUSIONS

A new low alloy steel powder, ATOMET 4701, was developed for sinterhardening applications. The sintered properties of this material were characterized for various concentrations of graphite and copper. The main conclusions for the test conditions used in this study are:

1. For a mix containing 2% copper, the as-sintered apparent hardness increases with graphite content to about 35 HRC in a conventional sintering furnace.
2. Tempering decreases the apparent hardness relative to the as-sintered condition. This difference is greater as the carbon and/or copper concentration and hence the proportion of martensite increases.
3. In the as-sintered state, tensile properties of compacts containing 2% copper are optimized at a carbon content of 0.5 to 0.6%. At higher carbon levels, the presence of untempered martensite deteriorates the tensile characteristics.
4. With 2% admixed copper, the tempered tensile properties are optimized at a carbon content of 0.7%. Ultimate tensile and yield strengths of 120 and 93 kpsi (825 and 640 MPa) respectively, are achieved after tempering for 60 minutes in air at 400°F (205°C).
5. The martensite proportion increases with copper and carbon concentrations up to 80% for compacts containing 0.85% carbon and 2% copper.

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