EFFECT OF DENSITY ON MECHANICAL PROPERTIES OF SINTER HARDENED P/M MATERIALS

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ABSTRACT

Sinter hardening is a cost effective process where P/M parts harden during the cooling phase of the sintering cycle, thus eliminating the need for post-sintering heat treatment. Sinter hardening requires materials with high hardenability. This is generally obtained with low alloy steel powders. The achievable mechanical properties depend on material composition, P/M part density and processing route.

A test program has been carried out to evaluate the effect of density on mechanical properties of a low alloy steel powder containing 0.45% Mn, 0.45% Cr, 0.90% Ni and 1.0% Mo admixed with 2.0% copper and either 0.65 or 0. 80 % combined carbon. Test specimens were pressed to 6.8, 7.0 and 7.15 g/cm³ as well as forged to full density. Green densities of 6.8 and 7.0 g/cm³ were achieved via cold compaction while warm pressing was used to reach 7.15 g/cm³. The sintering was carried out at 1120°C for 25 minutes in a nitrogen based atmosphere. Apparent hardness was measured in the as-sintered condition and after tempering at 205°C for 60 minutes.

Apparent hardness increased almost linearly with density for both carbon concentrations. The effect of density was more pronounced with the 0.65% C materials and both materials showed similar hardness at full density. A reduction of apparent hardness of about 5 HRC was observed on tempered specimens. Ultimate tensile and yield strength also increased linearly with density for both carbon concentrations. Highest strength values were obtained with the 0.65% C material.

INTRODUCTION

High strength and high apparent hardness P/M parts can be produced by sinter hardening when a martensitic structure is obtained in the sintering furnace as the parts are cooled from the sintering temperature. Sinter hardening thus eliminates the need for post-sintering heat treatment. The amount of martensite produced during sinter hardening is a function of the alloy hardenability, the cooling capacity of the sintering furnace and the section thickness of the parts. Therefore, with a good knowledge of the cooling rate encountered by the P/M parts after sintering, the mix formulation can be adjusted to tailor specific microstructures and properties.

To obtain a homogeneous microstructure at conventional sintering time and temperature, the use of prealloyed steel powders is generally preferred to the admixing of elements such as nickel, molybdenum or ferro alloys. This generally results in higher mechanical properties for comparable alloying additions [1,2]. This has been demonstrated with the development of a low alloy steel powder specifically designed to sinter harden in conventional sintering furnaces thus allowing the production of high strength and high apparent hardness parts even with a relatively slow cooling rate [3]. Previous work published on this new sinter hardening material described its properties as a function of sintering and tempering conditions, at a constant apparent density level of about 6.8 g/cm^3 [4,5]. However, the density is expected to significantly affect properties of sinter hardened parts because residual porosity reduces strength as well as the heat transfer and cooling rate after sintering. The present work was thus carried out to study the effect of density within the range of 6.8 to 7.7 g/cm^3 on the hardness and strength of sinter hardened and tempered specimens.

EXPERIMENTAL PROCEDURE

The base powder used in this study was ATOMET 4701, a low alloy steel powder specifically designed for sinter hardening applications. Table 1 shows the typical physical and chemical properties of this powder. Mixes were prepared with 2% copper and either 0.85 or 1.0% graphite to reach carbon concentrations of 0.65 and 0.80% respectively in the test pieces after sintering. All powder mixes contained 0.5% lubricant. A series of test pieces were cold compacted to either 6.8 or 7.0 g/cm^3. Warm compaction at 150°C was used to prepare specimens in the 7.15-7.17 g/cm^3 density range. The specimens were sintered at 1120°C for 25 minutes in a 90% nitrogen based atmosphere. The cooling rate was 0.7°C/s from 870 to 650°C and 0.4°C/s from 650 to 400°C. Sintered preforms of 4 in. diameter were also forged to full density. Sections measuring 1.5 inches in thickness, 0.5 inch in width and 2.5 to 4 inches in length were prepared from these disc specimens. These pieces were subsequently full annealed, machined into round tensile and Charpy specimens and reprocessed in the sintering furnace to obtain the same cooling rate experienced by the sintered specimens. All the specimens were tempered one hour in air at 205°C. The tensile properties were determined using round machined specimens per MPIF standard 10 while impact energy was measured using un-notched Charpy specimens according to MPIF standard 40.

TABLE 1
Physical and chemical characteristics of ATOMET 4701.

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

RESULTS AND DISCUSSION

Figure 1 illustrates the effect of density on apparent hardness of specimens containing 0.65 and 0.80% C in the as-sintered condition and after tempering 60 minutes at 205°C. As expected, the apparent hardness increases with density for both carbon concentrations. After tempering, the apparent hardness drops by about 5 HRC. As illustrated in Figure 2, the microstructure is mainly composed of martensite with areas of bainite and some retained austenite. The martensite content is higher in the high carbon specimens for the various densities studied. Image analysis confirmed that the proportion of martensite was about 10% higher in the 0.80% C specimens as compared to the 0.65% C specimens. A difference of about 15% in martensite content was also measured between the forged specimens and those in the 6.8 to 7.15 g/cm³ density range, the dense specimens exhibiting the highest proportion of martensite. It is also worth noting that the slope of the curves in Figure 1 for the 0.65% C are steeper than that of the 0.80% C. At low density, the apparent hardness of the high carbon specimens is higher than the 0.65% C specimens by about 6 HRC. This difference gradually decreases as the density increases and both materials show similar hardness values i.e. 60 and 55 HRC for the as-sintered and tempered conditions. For wrought steels, the hardness of martensite increases rapidly with carbon content up to about 0.4% and tends to level off beyond this point because of the greater tendency to form retained austenite in high carbon steels [6]. This may explain why there is no difference in hardness between both carbon contents for the fully dense specimens. However, at lower density, porosity reduces the heat transfer which in turn favors the formation of bainite rather than martensite. This may explain the larger difference in hardness as the density is decreased.

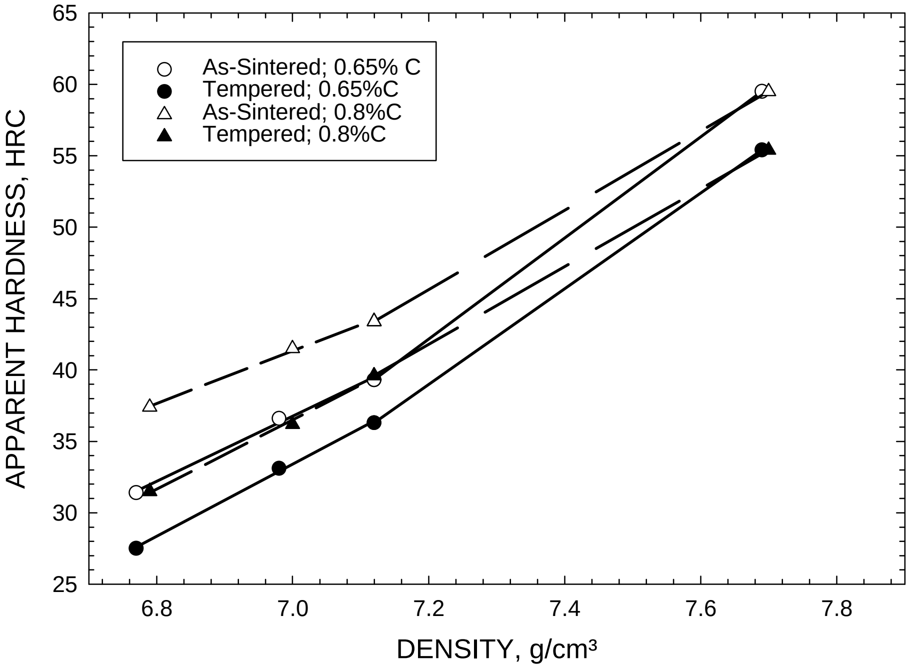

Figure 1. Effect of density and carbon content on apparent hardness of sinter hardened specimens in the as-sintered conditions and after tempering 60 minutes in air at 205°C.

The effect of density and carbon content on ultimate tensile strength (UTS) is illustrated in Figure 3. Similar to apparent hardness, there is also a linear correlation between UTS and density for both carbon contents. The slope for the lower carbon curve is also steeper than that of the 0.80%C. At 6.8 g/cm^3, both materials show a similar tensile strength of about 900 MPa (130,000 psi). However, as the density increases, specimens at 0.65% C show a higher strength relative to 0.80% C and the difference is larger at full density. The forged specimens containing 0.65% C reach a tensile strength of 2050 MPa (300,000 psi). This value is similar to that of AISI 8660 steels (0.6% C, 0.88% Mn, 0.55% Ni, 0.50% Cr and 0.20% Mo) after quenching and tempering.

Figure 4 illustrates the effect of density and carbon content on yield strength (YS). Again, a good linear relationship is found between YS and density for both carbon concentrations. As for the UTS, the slope of the curve of the 0.65% C specimens is steeper than that of specimens containing 0.80% C. The lower carbon content materials show a higher YS throughout this density range. The difference in YS between the medium and high carbon materials is larger at higher density. It is 50 MPa at 6.8 g/cm^3 and 370 MPa at full density.

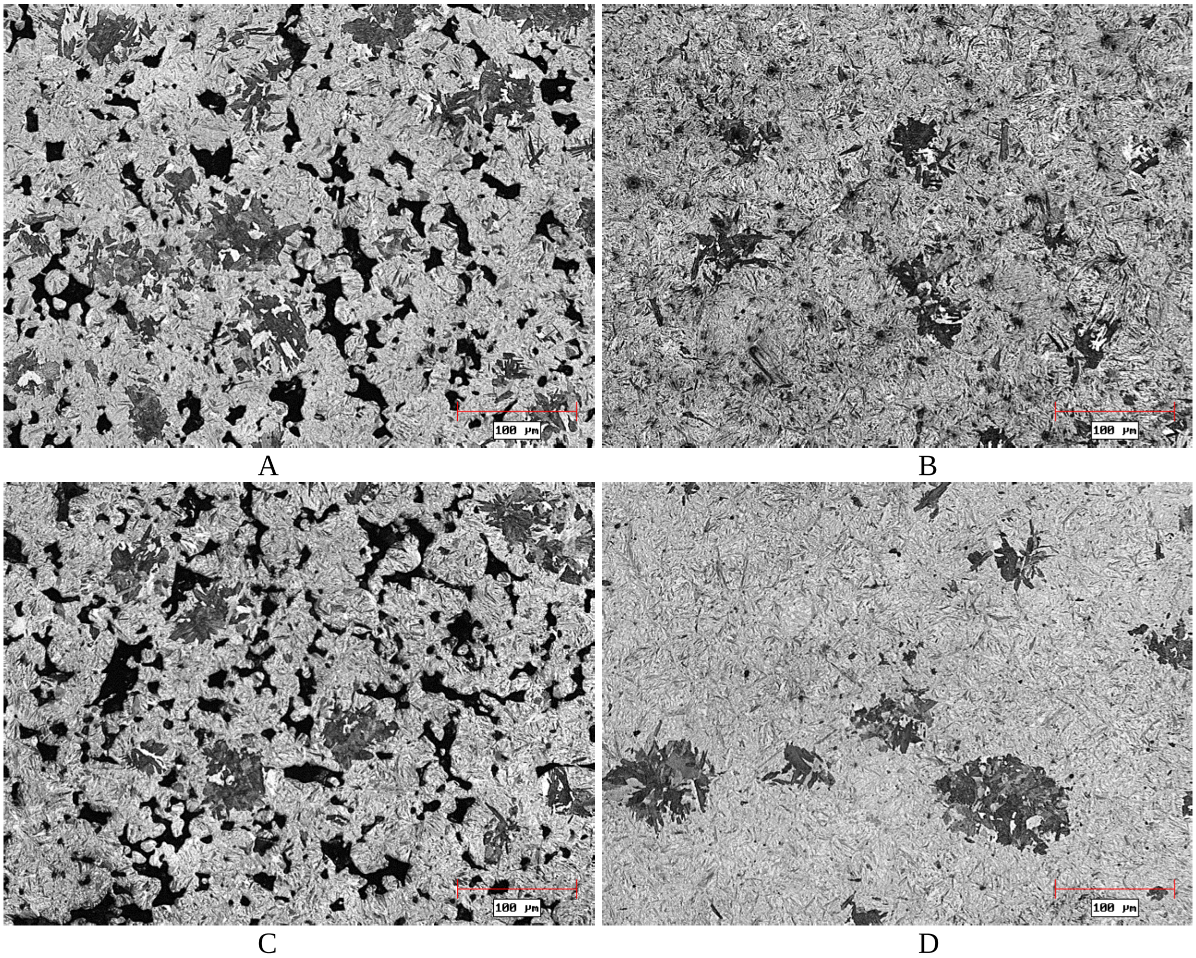

Figure 2. Microstructure of specimens after etching (Nital 2%).

A) 0.65% C; sintered density of 6.77 g/cm^3.
B) 0.65% C; density of 7.70 g/cm^3.
C) 0.80% C; sintered density of 6.79 g/cm^3.
D) 0.80% C; density of 7.69 g/cm^3.

Figure 5 illustrates the effect of density on elongation for the two carbon concentrations. Below 7.2 g/cm^3, both materials exhibit elongation values close to or less than 1%. Higher elongation values are obtained with the forged specimens but are generally lower than that of conventional steels. Finally, lower elongation values are generally obtained for the high carbon specimens.

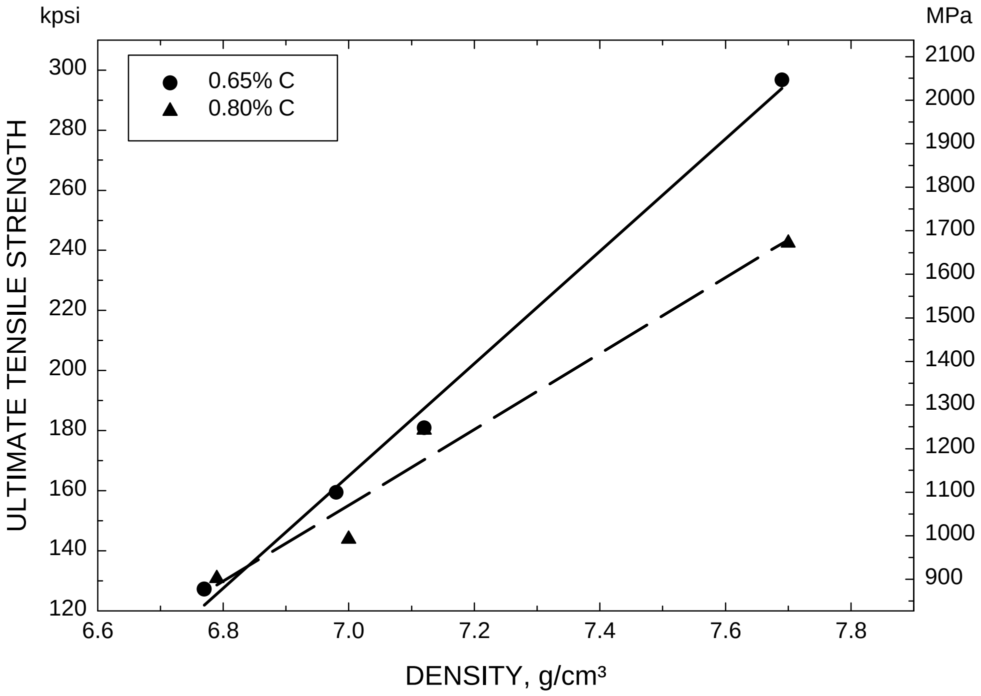

Figure 3. Effect of density and carbon content on ultimate tensile strength of sinter hardened and tempered specimens.

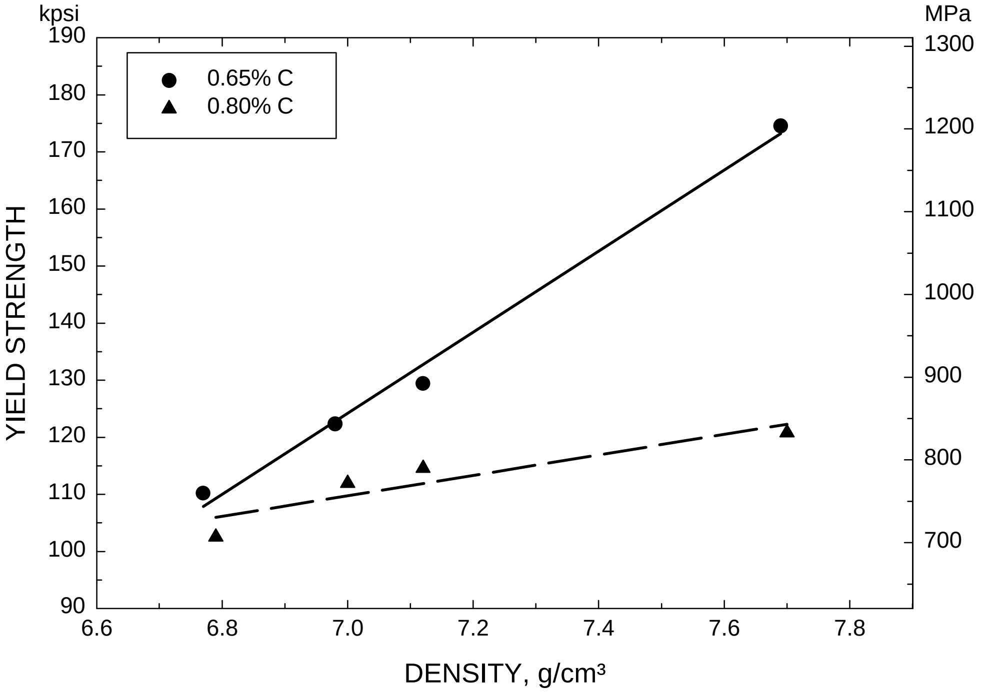

Figure 4. Effect of density and carbon content on yield strength of sinter hardened and tempered specimens.

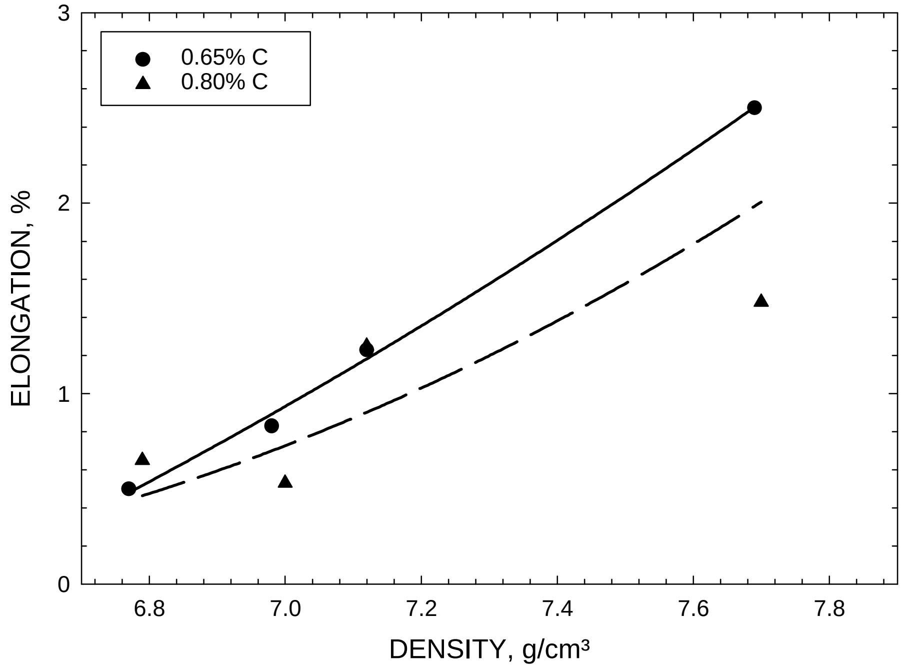

Figure 5. Effect of density and carbon content on elongation of sinter hardened and tempered specimens.

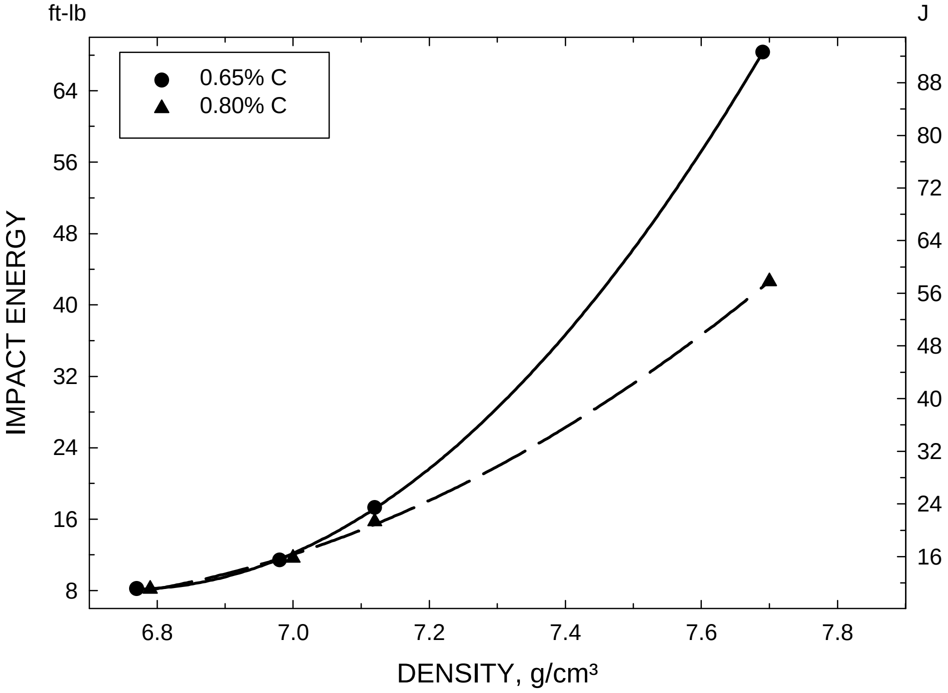

Figure 6. Effect of density and carbon content on impact energy of sinter hardened and tempered specimens.

The effect of density on impact energy is illustrated in Figure 6 for both carbon concentrations. Impact energy increases exponentially with density. Below 7.15 g/cm³, both the 0.65 and 0.80% C materials exhibit very similar impact energy values. However, at higher densities, higher impact energy values are achieved with the lower carbon material. Impact energy readings of 90 joules (70 ft-lb) were obtained with the forged specimens containing 0.65% C

CONCLUSIONS

1. Apparent hardness increased with density for both the 0.65 and 0.80% C materials. The rate of increase as a function of the density was larger with the 0.65% C material.

2. The tempering treatment of 60 minutes at 205°C reduced apparent hardness by about 5 HRC for both carbon concentrations.

3. UTS and YS increased linearly with the density for both carbon concentrations. The lower carbon material exhibited the highest strength, particularly at high density. The UTS of the material containing 0.65% C increased from 900 MPa (130,000 psi) at 6.8 g/cm³ to 2050 MPa (300,000 psi) at 7.7 g/cm³.

4. Both materials showed lower elongation values even in the fully dense state compared to conventional steels.

5. Impact energy increased rapidly with density for both carbon concentrations. Below 7.15 g/cm³, both materials exhibited similar impact energy but above this density, the 0.65% C material showed a significantly higher impact resistance.

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