Effect of Porosity on the Thermal Response, Hardness, Hardenability, and Microstructure of P/M Steels

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Abstract:

The pores present in sintered steels affect their thermal characteristics. In the present study the role of porosity was examined in two hybrid P/M steels in relation to cooling rate, hardness, hardenability, and microstructure utilizing an instrumented Jominy test. To establish a base line for thermal response in the absence of pores, Jominy bars were hot isostaticlly pressed after sintering. Pores enhance slightly the measured cooling rate near the water quenched end of the Jominy bar. This behavior is predicted on the basis of a recent simple heat transfer model in which a decrease in thermal diffusivity results in faster cooling near the water quenched surface. Alternatively, simulation of penetration of water into the pores by capillary action predicts that this is a viable mechanism to enhance cooling rate.

Introduction:

Pores in sintered steels influence their thermal response and hardenability (1-8). In a recent study by Saritas, et al. (9) the Jominy end-quench test of a sintered steel was simulated by means of a three-dimensional finite difference model in which porosity in the range 2.5 v/o to 20 v/o was introduced in the form of randomly selected points treated as cubic pores. The model predicted that the cooling rate was lowered in the presence of pores. Experimental data from instrumented Jominy tests on sintered steels showed that the steels with porosity levels >10 v/o cooled more rapidly than a wrought steel of similar composition. This contradiction between the prediction of the model and the measured thermal response of the powder metallurgy (P/M) steels was attributed tentatively to water penetration via interconnected pores with an attendant increase in cooling rate.

In a subsequent study, Stiles (10) used the instrumented Jominy test to measure cooling rates in sintered steels of the same composition as those used by Saritas et al (9) after sealing the surface by shot peening to preclude the possibility of water penetration. The shot peened Jominy bars cooled more slowly and exhibited a higher hardenability than the Jominy bars that were not shot peened. However, the hardness levels after shot peening exceeded those of the Jominy bars that were not shot peened. These observations can be explained by decarburization in the Jominy bars that were not shot peened and/or surface densification as a result of shot peening.

The objective of the present study was to resolve the role of pores in relation to cooling rate, hardness, and hardenability in these sintered P/M steels and assess the validity of the models based on simulation of the thermal conditions in a Jominy bar. To this end, the instrumented Jominy tests were repeated on the P/M steels after which parallel flats were ground to a depth sufficient to remove any material densified by shot peening or subjected to decarburization. In addition, microstructures of the quenched Jominy bars were characterized on cross-sections at which the cooling rate was measured. To establish a base line for the thermal response of the P/M steels in the pore-free condition, Jominy bars of the sintered steels were hot isostatically pressed.

Experimental Procedure:

Materials:

The compositions of the two P/M steels evaluated are listed in Table I. Water atomized Hoeganaes Ancorsteel 85HP[*] was used as the base iron powder. Premixes were made without lubricant because the test samples were compacted by cold isostatic pressing (CIP). The lubricant reduces green strength and green density and is not necessary since die ejection is not integral to CIP.

Table I: Alloy Compositions

*Alloy**	*Base Material*	*Graphite (w/o)*	*Ni (w/o)*	*Cu (w/o)*
FLC2-4405	Ancorsteel 85HP	0.6	-	2.0
FLN2-4405	Ancorsteel 85HP	0.6	2.0	-

*Metal Powder Industries Federation, Princeton, NJ, Standard 35 Designation

Jominy End-Quench Specimen:

Jominy end-quench bars were prepared which complied with ASTM standard A255-99. Oversized cylinders were compacted by CIP at 414 MPa (60,000 psi). The green cylinders were then sintered at 1120ºC (2050ºF) for 30 min in 75 v/o H_2 - 25 v/o N_2. This resulted in a sintered density of about 6.9 g/cm^3, with a corresponding porosity level in the range 9.0 v/o - 10.0 v/o for both steels. Subsequently, the samples were machined to finished size and subjected to the secondary processes listed in Table II.

Table II: Secondary Processing

Processing Condition	*Description*
As-sintered	None
Shot Peened	Peening to near-surface full density at quenched end and along cylindrical surface for a distance 25.4 mm (1.0 in.) from quenched end.
HIP	Hot isostatic pressing (HIP) to full density at 1065°C (1950°F) and 103 MPa (15,000 psi) for 4 h. at temperature.

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[*] Ancorsteel 85HP is a registered trademark of Hoeganaes Corporation.

Holes 0.84 mm (0.03 in.) dia. were drilled at distances of 5 mm (0.2 in.), 25 mm (0.98 in.), 45 mm (1.77 in.), and 65 mm (2.56 in.) from the water-quenched end for the insertion of thermocouples. Figure 1 shows a schematic of the thermocouple arrangement.

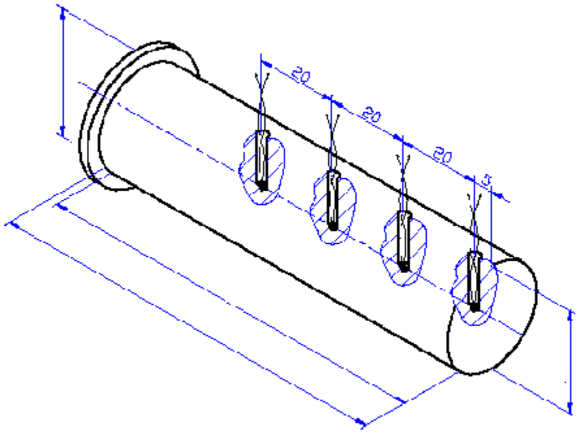


Figure 1: Instrumented Jominy specimen-schematic.

Jominy End-Quench Test:

All samples were tested according to ASTM standard A255-99. The Jominy bars were austenitized at 900°C (1650°F) for 30 min. in an atmosphere of 75 v/o H_2 - 25 v/o N_2 prior to quenching. Temperature measurements during the water quench were recorded at 1 s intervals until the bar reached approximately 45°C (110°F).

After quenching, parallel flats were ground along the length of the Jominy bar. Since the hardness levels of these alloys are at the upper end of the Rockwell HRB scale and at the lower end of the HRC scale, the Rockwell HRA scale was used for apparent hardness. Apparent hardness traces were made on both flats and then averaged.

Metallography:

After Jominy end-quench testing, samples were sectioned for optical metallography to examine the pore structure and the microstructural products of transformations. Cross-sections perpendicular to the axis of quenching were examined at selected distances from the water quenched end of the bars. Photomicrographs were taken in the as-polished and as-etched conditions. The etchant was a 2.0 v/o nitric acid - 4.0 v/o picric acid solution.

Results:

Cooling Curves:

Cooling curves for the two P/M steels tested are shown in Figure 2. These experimental plots were determined at a distance of 5 mm (0.2 in.) from the water quenched end of the Jominy bars. The data show that for both alloys, the Jominy bars that were sealed by shot peening or HIP'ed to full cool at a lower rate than the as-sintered bars. This is demonstrated by the shift upward of the curves beyond 50-75 s for the HIP'ed and shot peened bars.

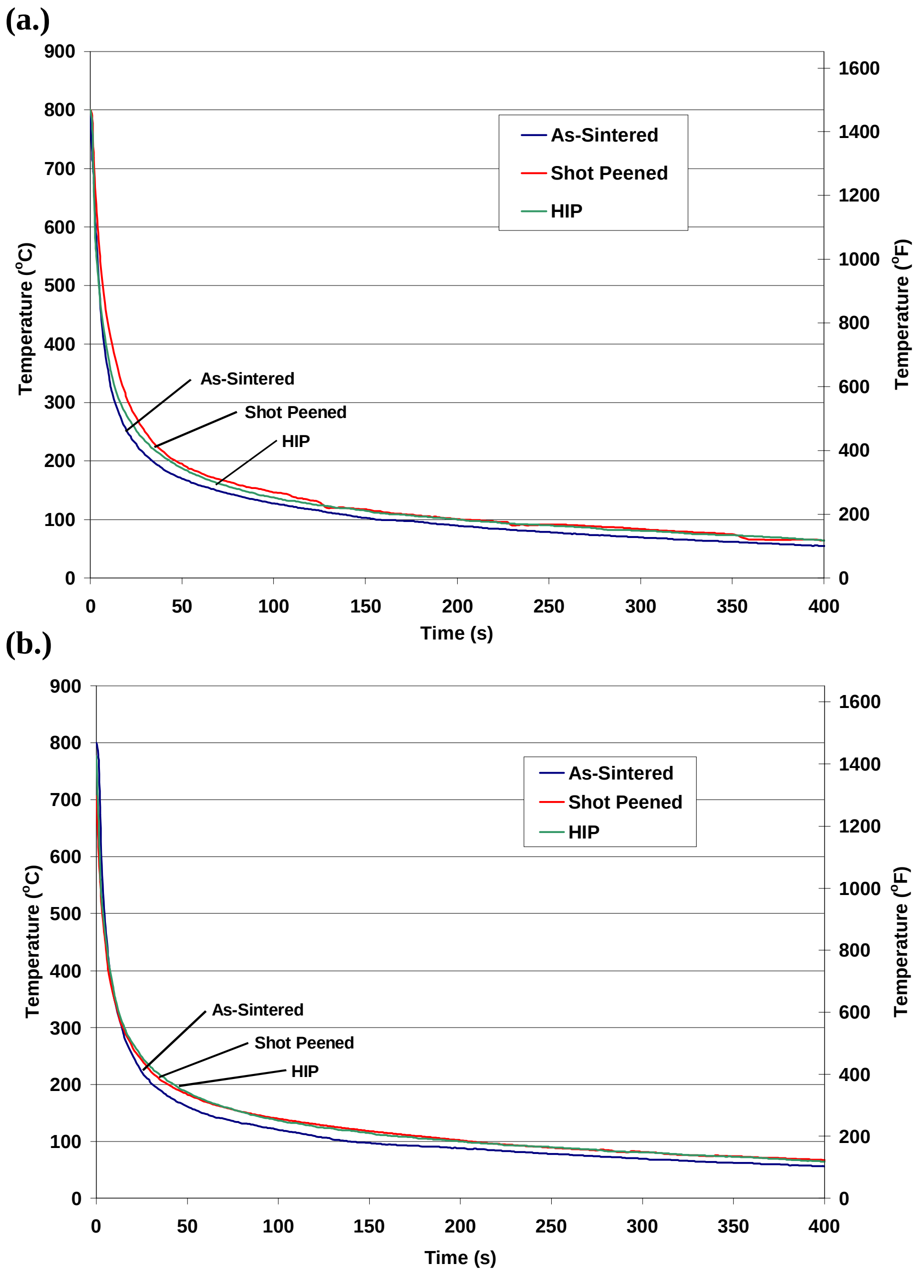


Figure 2: Cooling rates of Jominy bars at 5 mm (0.2 in.) from the water quenched end: (a.) FLC2-4405, and (b.) FLN2-4405.

Jominy Hardness Traces:

Jominy hardness traces are shown in Figure 3 for the two P/M steels. The plots do not include hardness data for the HIP'ed condition. The reason for this omission is that the HIPing cycle increases density, which increases apparent hardness. In addition, the

HIPing cycle involves a 4 h holding period at 1065°C (1950°F), during which time diffusion of the alloying elements occurs with a change microstructure and attendant grain growth.

For the both P/M steels the initial hardness is higher in the shot peened Jominy bars than in the Jominy bars with open pores to a distance of about 38.1 mm (1.5 in) from the water quenched end. Beyond this distance from the water quenched end, the hardness traces converge. This indicates that the flats were not ground deeply enough to avoid completely the densified layer that was produced by shot peening. For the Ni steel, there is a slight disparity of about 2.0 HRA in the hardness levels for the two conditions. This can be attributed to a small difference in total porosity in the bars.

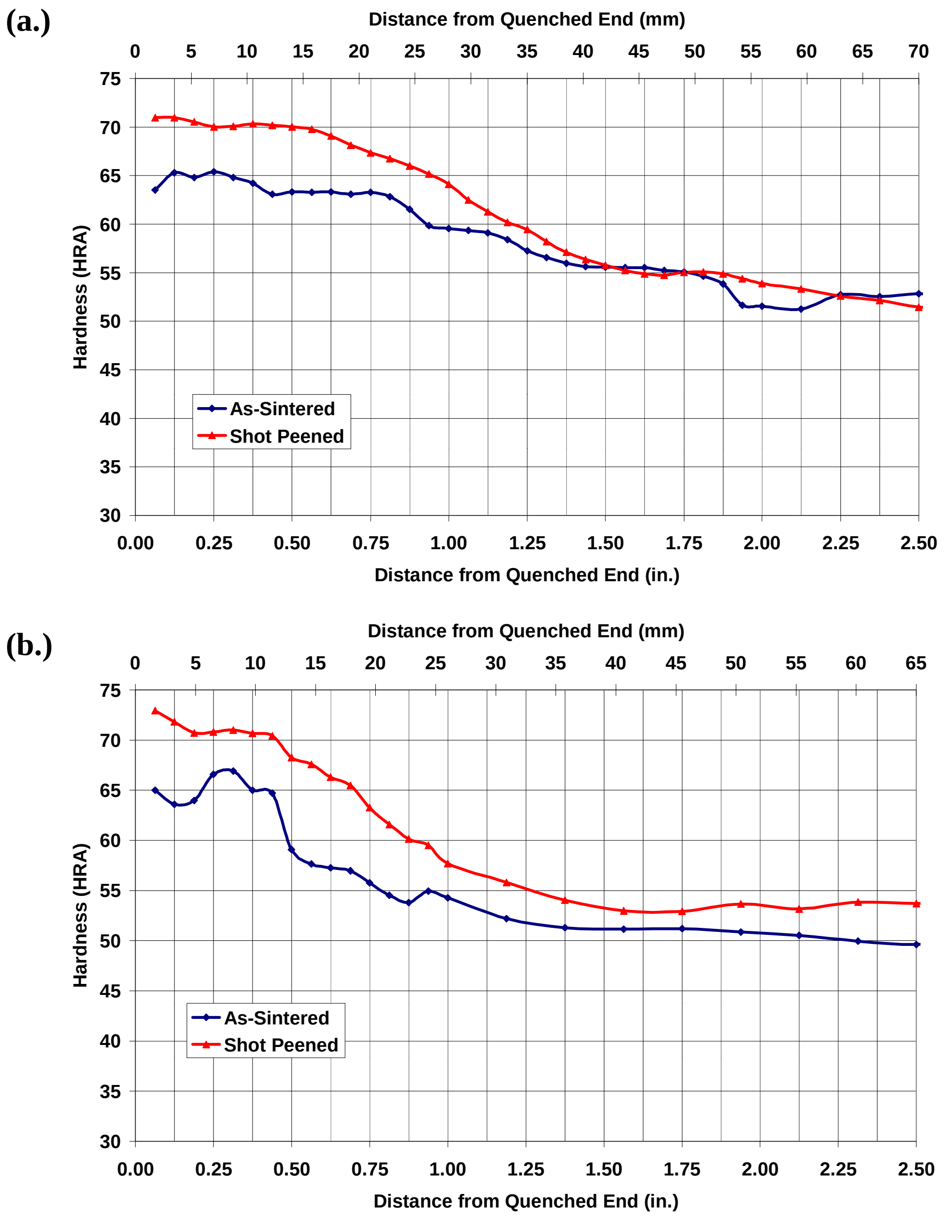


Figure 3: Hardness traces for Jominy bars: (a.) FLC2-4405, and (b.) FLN2-4405.

The difference in apparent hardness between the hardness traces of the as-sintered and the shot peened bars lends uncertainty to the actual apparent hardness at a given distance in the core. To resolve this question, the Jominy bars were sectioned at selected distances from the water quenched end and apparent hardness measurements were taken at approximately at the center line. The hardness data are summarized in Table III. The data show that the difference in apparent hardness at the core of the Jominy bars in the as-sintered and the shot peened conditions is less than 2 HRA at distances up to 25.4 mm (1.0 in) from the water quenched end. This is well within error of measurement for the Rockwell hardness test and confirms that there is no significant difference in hardness at the core of the Jominy bars.

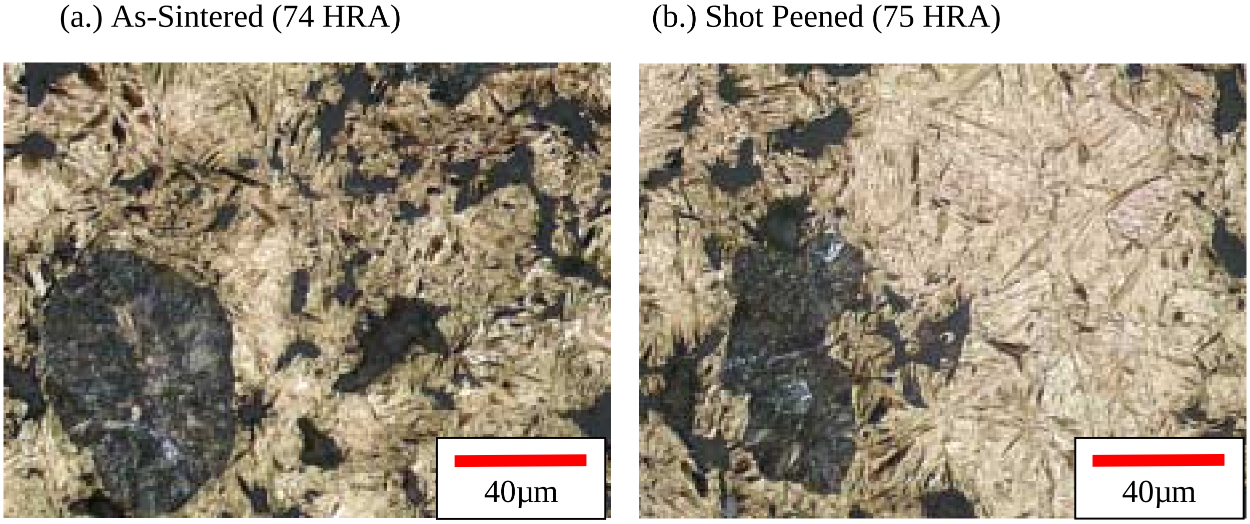
Table III: Apparent Hardness (HRA) at Core of Jominy Bars

Alloy/Condition	***Quenched End***	***5 mm* (0.2 in)***	***15 mm* (0.6 in)***	***25mm* (0.98 in)***
FLC2-4405 As-sintered	75	74	71	63
FLC2-4405 Shot Peened	74	75	70	66
FLN2-4405 As-sintered	68	68	61	56
FLN2-4405 Shot Peened	70	68	62	58

*Distance from the water quenched end of Jominy Bar

Metallography:

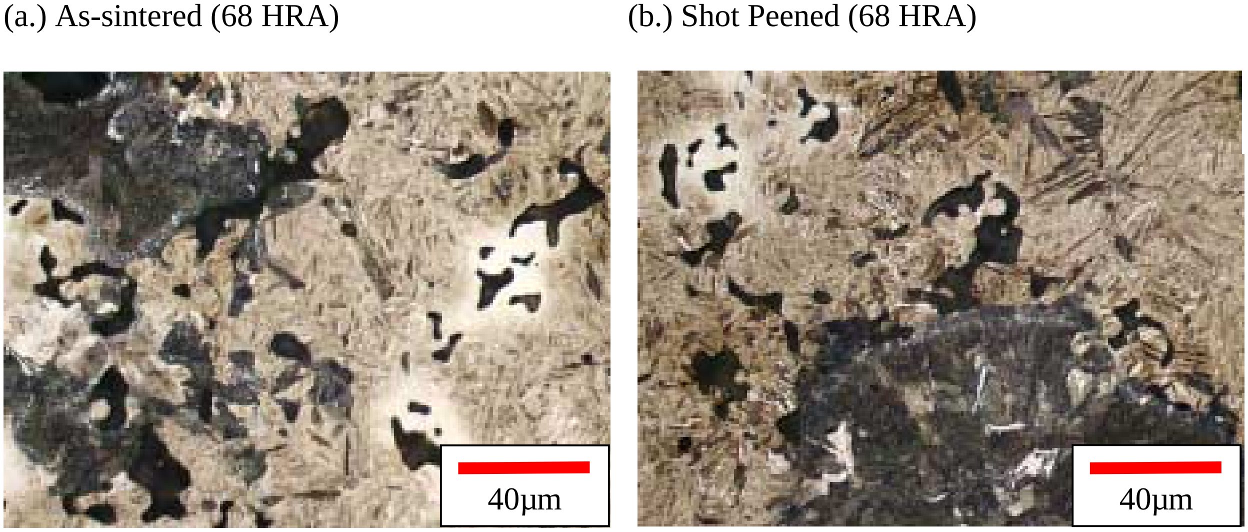
Photomicrographs were taken in areas adjacent to those at which hardness measurements were performed. Figure 4 shows a comparison of representative microstructures of the as-sintered and shot peened FLC2-4405 steel Jominy bars at a distance of 5 mm (0.2 in) from the water quenched end. The microstructures in the two conditions are similar. Primary constituents are lath martensite and retained austenite; there is also some bainite present.


(a.) As-Sintered (74 HRA)

(b.) Shot Peened (75 HRA)

Figure 4: Microstructures of FLC2-4405: (a.) as-sintered, and (b.) shot peened, Etch: 2.0 v/o nitric acid - 4.0 v/o picric acid; optical micrographs.

Representative micrographs of the FLN2-4405 steel Jominy bars are similar in the as-sintered and shot peened conditions at 5 mm (0.2 in) from the water quenched end, Figure 5. The microstructure consists of lath martensite interspersed with retained austenite, bainite, and regions of Ni-rich martensite. The hardness of the Ni-steel is about 6 HRA lower than that of the Cu-steel.


(a.) As-sintered (68 HRA)

(b.) Shot Peened (68 HRA)

Figure 5: Microstructures of FLN2-4405: (a.) as-sintered, and (b.) shot peened, Etch: 2.0 v/o nitric acid - 4.0 v/o picric acid; optical micrographs.

Discussion:

The hardness levels (Table III) and microstructures (Figure 4) of FLC2-4405 are similar in the as-sintered and shot peened conditions at 5 mm (0.2 in.) from the water quenched end. Thus, the attendant cooling rates cannot be too different in the two conditions. A similar conclusion is drawn for FLN2-4405, based on the hardness levels in Table III and the microstructures in Figure 5. The higher hardness of the copper-containing alloy (75 HRA) compared to the nickel-containing alloy (68 HRA) is attributed to incomplete diffusion of the nickel after sintering.

Though relatively small, the differences in measured cooling rates in both P/M steels in the as-sintered, shot peened, and HIP'ed conditions (Figure 2) are considered accurate. Why does the as-sintered Jominy bar cool at a higher rate than the shot peened or HIPed Jominy bars at a distance of 5 mm (0.2 in.) from the water quenched end?

Based on a simple heat transfer model Zavalinangos et at (11) have recently demonstrated that a reduction in thermal diffusivity results in an increase in the cooling rate near the water quenched end of a Jominy bar, but results in a decrease in cooling rate in the bulk of the material. Model predictions are shown in Figure 6 using parameters and properties applicable to wrought AISI 4150 wrought steel. The modeled reduction in thermal diffusivity was 10% and the calculation was for a distance of 5 mm (0.2 in.) from the water quenched end of the bar. The cooling curves in Figure 6 are consistent with the positions of the cooling curves for the as-sintered, shot peened, and HIP'ed P/M steels in Figures 2(a) and 2(b).

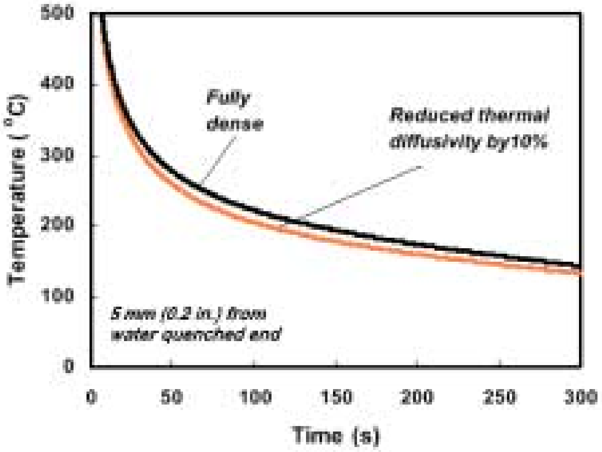


Figure 6: Effect of reduced thermal diffusivity on cooling response of wrought AISI 4150 steel at 5 mm (0.2 in.) from the water quenched end.

In the same modeling study (11) a model was also formulated to examine the possibility of enhanced heat transfer due to water penetration into the pores of a sintered steel by capillary action. The model predicts that penetration of water into the pores can occur and that this mechanism contributes to an enhanced cooling rate relative to the fully dense steel. For example, after 100 s, a water penetration depth of ~10 mm (0.4 in.) is predicted at 10 v/o porosity.

In relation to the cooling rates determined in the present study on the two P/M steels, either or both effects (reduction in thermal diffusivity / water penetration by capillary action) may be operative. Because of the small magnitude of the difference in cooling rate, it would be extremely difficult to differentiate between each mechanism.

Conclusions:

1. Hardness levels and microstructures in quenched Jominy bars of copper-containing and nickel-containing steels are similar in the as-sintered and shot peened conditions with the inference that attendant cooling rates are not too different.
2. For both the copper-containing and nickel-containing steels, cooling rate is higher in the as-sintered condition than in the shot peened or HIP'ed conditions, as measured via an instrumented Jominy test.
3. Based on a simple heat transfer model, cooling rate increases with decreasing thermal diffusivity near the water quenched end of a Jominy bar. The opposite effect is predicted in the bulk of the bar. These model predictions are consistent with the measured cooling rates in the as-sintered, shot peened, and HIP'ed P/M steels.

4. From a simulation of water penetration into pores via capillary action, it is predicted that this mechanism is possible, with an attendant increase in cooling rate.

Acknowledgement:

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