THE HARDENABILITY OF SOME P/M MATERIALS: AN EVALUATION THROUGH AN INSTRUMENTED JOMINY TEST

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Abstract
For any industrial application, in order to avoid large and unexpected structural variations which could result in unpredictable and unacceptable strength decreases, knowledge of the maximum dimensions allowed for a mechanical part is fundamental. This basic need is summarized in the concept of "hardenability", well known and widely used for fully dense steels. Using the procedure standardized by the Jominy end-quench test, the hardenability of some sintered steels has been measured on samples of specific dimensions and shape. Hardenability curves were obtained for steels based either on pre-alloyed or diffusion-bonded powders. The test pieces were produced by compaction at two different densities and sintering at 1120°C for 30 minutes, in industrial equipment. In order to investigate the thermal behavior of the experimented PM steels, temperatures inside the Jominy sample, at specific positions, were recorded during cooling after austenitizing. These measurements, together with the achieved hardenability curves, give important information which is suitable for predicting the microstructure in components of various dimensions, cooled after sintering at different rates.
Keywords: hardenability, ideal diameter P/M steel, sinter hardening

INTRODUCTION

According to ASM, [1], hardenability is "The relative ability of a ferrous alloy to form martensite when quenched from a temperature above the upper critical temperature. Hardenability is commonly measured as the distance below a quenched surface at which the metal exhibits a specific hardness (50 HRC, for example) or a specific percentage of martensite in the microstructure. "Still, according to ASM" [2]. The hardenability of steel is governed almost entirely by the chemical composition (carbon and alloy content) at the austenitizing temperature and the austenite grain size at the moment of quenching." From the former definition, it follows that a high depth of martensitic structure corresponds to high hardenability values of the steel. Two methods are available for the hardenability measurements: Grossman test and Jominy test.

The Grossman method [3,4] is based on the measurement of the critical diameter, defined as the diameter of a cylinder which shows 50 % of martensitic structure at its centre, when quenched in a defined cooling medium. The critical diameter depends both on the material and on the cooling rate (H): for a given steel, the higher the cooling rate the higher the critical diameter is. The critical diameter obtained with an infinite cooling rate ($H = \infty$) is called ideal diameter. The ideal diameter is a property of the material. It can be calculated from the chemical composition and the dimensions of the austenitic grains. The knowledge

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of the ideal diameter allows the calculation of the critical diameter for a given cooling rate. The measurement of the ideal diameter presents several experimental difficulties. The latter derive from the need of quenching many cylinders with a length more than twice the diameter, and then evaluating the amount of martensite present in each cylinder. The Jominy method [5] is most commonly used to measure the hardenability of the steel, owing to its simplicity, so that it has been standardised by EN ISO [6] and ASTM [7]. While for fully dense steels the literature data cover a wide variety of grades [4 - 7], for PM steels the database seems to be limited to recent years [8-14]. Also for P/M steels, the hardenability depends on:

- the chemical composition, that can be uneven, depending on powder used and processing conditions;
- the austenitic grain size, depending on sintering conditions;
- the cooling rate achieved inside the samples, which depends on chemical compositions and density of the material.

It is well known that the main differences between P/M materials and the fully dense ones are the presence of porosity and, in many cases, the typical heterogeneity of chemical compositions when the materials are achieved from mixes of elemental powders or from diffusion-bonded powders [15].

Over a long period, experience demonstrated that porosity influences conductivity of porous materials. Then, porosity influences the thermal behaviour of P/M steels [14, 16, 17, 18]. A consolidate experience demonstrated also that the chemical composition influences the position of the CCT curves and hence the hardenability of P/M steel directly. Due to the growing interest in sinter hardening, the knowledge of hardenability of PM steels is becoming more and more important. This knowledge is needed to answer the basic question about the maximum part weight that can be considered suitable for sinter hardening. On this basis, an experimental research was carried out, focused on microstructure and microhardness distribution inside parallelepipeds of constant cross-section and different heights. The first samples were obtained from a traditional sinter-hardening diffusion-bonded powder [19]. In this new research, the hardenabilities of some ferrous base powders have been determined through the Jominy end-quench test. Hardenability curves have been obtained for pre-alloyed and for diffusion-bonded powders as well. The investigated raw materials were either specific for sinter hardening or formulated for secondary heat treatments. The samples were compacted at two different densities and sintered at 1120°C for 30 minutes in industrial equipment. The ideal diameters have been calculated for each material, through the data available for fully dense steels and the obtained Jominy curves [6,7]. The different responses offered by different alloys and alloying methods enable one to define the maximum part volume that can be considered compatible with sinter hardening. The experimental results can help design engineers to make the optimum choice among available materials.

MATERIALS AND METHODS

The chemical composition of the base powders and the corresponding material' codes are reported in Tab.1. After mixing with 0.7 % graphite and 0.75 % lubricant, parallelepipeds with cross section (65 x 65 mm^2) and 63 mm height were compacted at two nominal densities: 6.8 g/cm^3 (coded -) and 7.0 g/cm^3 (coded +). The samples were sintered in industrial sinter-hardening equipment, at 1120°C for 30 minutes, under endogas from methane, and fast cooled at about 1°C/s in the temperature range from 800°C to 350°C. The carbon potential inside the furnace was set at 0.65 ÷ 0.7 % C. The parallelepipeds were divided into four parts. From each quarter, by turning, a cylinder was achieved; the dimensions were: diameter 25 mm and height 63 mm. Then, on each cylinder, a threaded hole was machined. This hole was made to make possible the insertion of a threaded extremity part, in order to observe the requirement of the standard, stating a total length equal to 100 mm [20]**.** Figure 1 shows how the probes for the Jominy test were cut from the original parallelepipeds. Each assembled set, porous probe and extremity parts, was machined by EDM to get 2 mm diameter holes. These holes, needed for K-type thermocouples, were made at equal radial position, half radius, but spaced at 120°. The depths of the holes were, respectively, 60, 50 and 40 mm from the upper face of the sinterhardened sample, to record the temperature transients at different distances from the quenched face. The instrumented Jominy probes were placed inside a muffle furnace, set at 900°C temperature, with an hour soaking time. Since no controlled atmosphere was available, to avoid carbon alteration the probes were placed inside small container, each one equipped with a graphite disc at the bottom. The temperature gradients also have been recorded during the heating stage, by the data-acquisition system Agilent 34970 A, connected to a personal computer. The acquisition frequency has been 1 Hz.

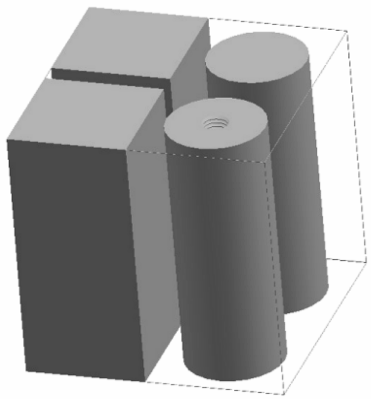

Fig.1. Schematic indications on the way used to take samples from the original parallelepipeds.

After cooling in the Jominy device, each probe has been ground, along 4 generatrices, to get the flat surfaces upon which to measure the hardness. The HRA scale has been used for evaluations and comparisons.

Tab.1. List of base powders used for the PM steels to be investigated.

Commercial Designation	Nominal Chemical Composition, [wt. %]							Material code
	Fe (a)	Ni (b)	Ni (c)	Mo	Mn	Cu (b)	Cu (d)	
Distaloy AE	94.00	4.00		0.50		1.50		AE
Astaloy Mo	98.50			1.50				AM
Distaloy HP	92.59	4.00		1.41		2.00		HP
Mannesmann MSP 4	94.25		4.00	0.55	0.20		1.00	M

(a) before copper, graphite and lubricant addition; (b) added by diffusion-bonding;
(c) added before atomisation; (d) added by mixing.

EXPERIMENTAL RESULTS

The Jominy curves have been drawn from the hardness values, following the indications of the standards. The hardness differences among the different faces of the samples are nil or definitely negligible. From the hardness profiles achieved from the Jominy test, and using the tables relevant to fully dense steels reported by the standards, the ideal diameters have been calculated. Then, assuming a severity index equal to 0.02 in^{-1}, following the estimates reported by [18], the critical diameters have also been calculated. They are reported in table 2. The hardenability bands are shown in Figs.2,3,4, and 5, where the distances from the quenched end are measured in mm. The bands have been represented with different greys: the brightest one corresponds to the higher density, the medium one corresponds to the lower density, while the darkest one corresponds to the overlap of the two bands.

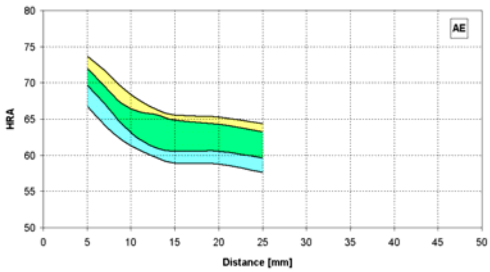

Fig.2. Hardenability bands for the P/M steel based on Distaloy AE powder.

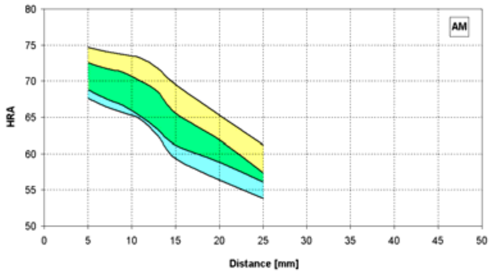

Fig.3. Hardenability bands for the P/M steel based on Distaloy Mo powder.

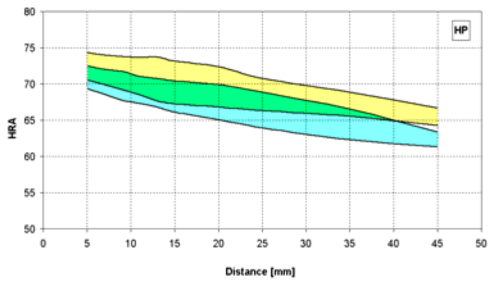

Fig.4. Hardenability bands for the P/M steel based on Distaloy HP-1 powder.

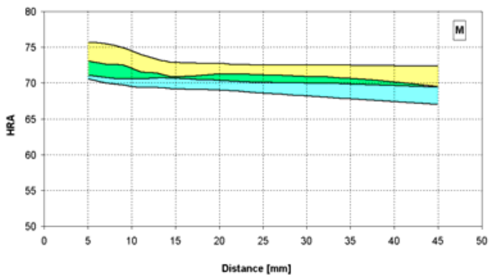

Fig.5. Hardenability bands for the P/M steel based on Mannesmann MSP4.

Tab.2. Ideal diameters, D_i, and critical diameters, D_{cr}

Material code	D_i [mm]	D_{cr} [mm]
AE	59	9
AM	70	10
HP	116	19
M	120	20

The comparisons between P/M steels obtained from homologous powders, at the higher nominal density, are presented in Figs.6 and 7. Of course, the higher hardenability of sinter hardening materials results are evident.

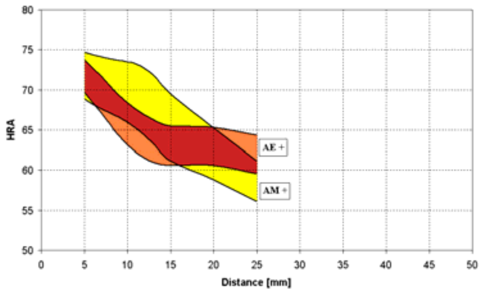

Fig.6. Comparison between hardenability bands for P/M steels based on Distaloy AE and Astaloy Mo powder.

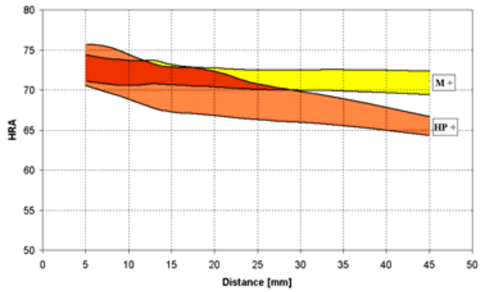

Fig.7. Comparison between hardenability bands for P/M steels based on Distaloy HP-1 and Mannesmann MSP 4 powder.

The results of microstructural investigations will be presented in an upcoming paper. Here, it may be interesting to specify that, on the samples based on Distaloy HP-1 powder, (6.8 g/cm^3 nominal density; Figs.8 and 9):

- at 3 mm from the quenched end martensite is the prevailing micro-constituent, with austenite, residual or partially transformed, more frequently located around pores;
- at 13 mm from the quenched end some bainite isles begin to appear, with still quite a lot of austenite;
- at 23 mm from the quenched end bainite isles become more frequent, evenly distributed, surrounded by a continuous austenite net.

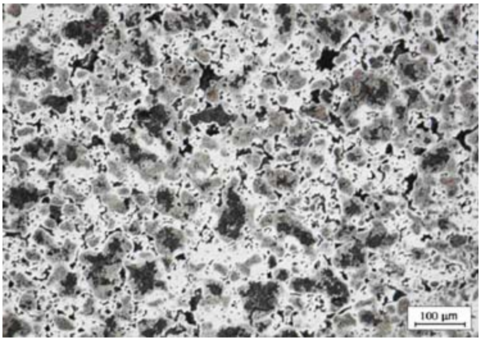

Fig.8. Steel from Distaloy HP-1 powder; microstructure at 23 mm from the quenched end.

Fig.9. Steel from Distaloy HP-1 powder; microstructure at 3 mm from the quenched end.

These microstructure changes are related to the different cooling speeds at different distances from the quenched end. The temperature curves at the above indicated distances, on the samples based on Distaloy HP-1 powder, (6.8 g/cm^3 nominal density) are plotted in Fig.10, while their derivatives are plotted in Fig.11.

The cooling rate in function of temperature reached at different distance from the quenched end can be related with the corresponding hardness and microstructure for the different materials.

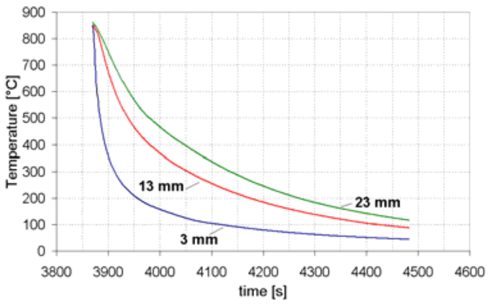

Fig.10. Temperature curves recorded by thermocouples located at different distances from the quenched end.

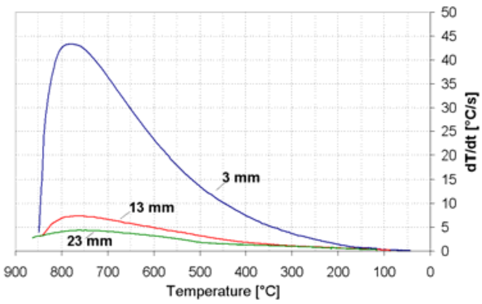

Fig.11. Derivatives of the temperature curves recorded by thermocouples located at different distances from the quenched end.

CONCLUSIONS

As already stated, the industrial exploitation of sinter hardening requires a quantitative knowledge about the hardenability of sintered steels. The hardenability of porous ferrous materials is a complicated function of chemical composition, compaction density, and sintering conditions. All things being equal, the final hardness also depends on actual cooling speed, and part geometry and weight. The Jominy test, usually applied for characterising fully dense steels, has also been applied to P/M steels. It is a rather simple test, apt to rate in a quantitative manner, the different suitability to hardening upon quenching, which is typical of differently formulated and processed P/M steels. Moreover, the test offers the possibility to record the temperature changes at various distances from the quenched end and the corresponding cooling speeds.

In summary, the research demonstrated that:

- The response of traditional P/M steels to water quenching is dramatically different from the response typical of materials expressly formulated for sinter hardening;
- The influence of density is conflicting. On one hand, a density increase increases the apparent hardness, whatever scale be used; on the other hand, a density increase reduces the material' thermal diffusivity, as already stated in [18]; the detailed results will be presented in an upcoming paper;
- A good correlation between the Jominy test and Grossmann test, repeatedly demonstrated for fully dense steels, holds true also for P/M steels;
- The knowledge of the ideal and critical diameters may be seen as an additional tool to make the optimum choice among different materials and processing conditions;

The hardness scale used to plot the hardenability of fully dense steel is the Rockwell C. In this paper, for a more sensible evaluation, the HRA scale has been preferred. This difference, of course, does not allow an immediate comparison of the numerical values, but does not invalidate any possible comparison among hardenability of P/M steels versus the comparable fully dense ones. On the same line, the hardenability plots presented here can be used to evaluate the maximum size of components apt for a correct treatment.

It should be pointed out that the HRA hardness scale, compared with the HRC one, may be preferred when the figures may be lower than 30. When this happens, with any Rockwell scale, the reliability and the possibility of data comparisons among different sources tend to decrease (This limitation is intrinsic of any Rockwell scale, because the hardness value is the result of a length difference).

The microstructural characteristics obtained on the different P/M materials investigated here will be presented in a future paper.

REFERENCES

[1] METALS HANDBOOK, Desk Edition. Eds. H. E Boyer, T. L. Metals Park : Gall American Society for Metals, 1985, p. 1-20
[2] METALS HANDBOOK, Desk Edition. Eds. H. E Boyer, T. L. Metals Park : Gall American Society for Metals, 1985, p. 4-58
[3] Grossman, MA.: Elements of Hardenability. Materials Park : ASM Int., 1952
[4] Grossman, MA., Bain, EC.: Principles of Heat Treatments. 5th Edition. Materials Park : ASM Int., 1964
[5] Jominy, WE., Bogehold, AL.: Trans. ASM, vol. 26, 1938, p. 574
[6] EN ISO 642, Steel – Hardenability test by end quenching (Jominy test)
[7] ASTM Test Method A255-02, Standard Test Methods for Determining Hardenability of Steel, American Society For Testing and Materials, West Conshohocken, Pennsylvania, 2002
[8] Lindskog, P.: Powder Metallurgy, vol. 13, 1970, no. 26, p. 280
[9] Eloff, P., Kaufman, S.: Powder Metallurgy Int., vol. 3, 1971, no. 2, p. 71
[10] L'Esperance, G., Harton, S., de Rege, A., Nigarura, S. In: Advances in Powder Metallurgy & Particulate Materials. Princeton : Metal Powder Industries Federation, 1995, p. 8-3
[11] L'Esperance, G., Duchesne, E., de Rege, A. In: Advances in Powder Metallurgy & Particulate Materials. Princeton : Metal Powder Industries Federation, 1996, p. 11-397
[12] Skena, C., Prucher, T., Czarnek, R., Jo, JM.: Int. J. Powder Metallurgy, vol. 33, 1997, no. 7, p. 25
[13] Duchesne, E., L'Esperance, G., de Rege, A.: Int. J. Powder Metallurgy, vol. 36, 2000, no. 1, p. 49
[14] Saritas, S., Doherty, RD., Lawley, A.: Int. J. Powder Metallurgy, vol. 38, 2002, no. 1, p. 31
[15] Bocchini, GF., Rivolta, B., Silva, G., Piccardo, P., Pinasco, MR., Poggio, E.: P/M Science & Technology Briefs, vol. 4, 2002, no. 4, p. 16
[16] Bocchini, GF.: Int. J. Powder Metallurgy, vol. 22, 1986, no. 3, p. 185
[17] Bocchini, GF., Rivolta, B., Silva, G., Ienco, MG., Pinasco, MR., Stagno, E. In: Advances in Powder Metallurgy & Particulate Materials. Princeton : Metal Powder Industries Federation, 2002, p. 13-60
[18] Bocchini, GF., Rivolta, B., Silva, G., Baggioli, A., Piccardo, P., Poggio, E. In: 2002 World Congress on Powder Metallurgy & Particulate Materials. Orlando, 16-21 June 2002
[19] Bocchini, GF., Baggioli, A., Rivolta, B., Silva, G. In: 19° Convegno Naz. Trattamenti termici. AIM, Salsomaggiore, 19-22 Maggio 2003
[20] UNI 3150-74, Prova di temprabilità dell'acciaio su provetta raffreddata ad una estremità (prova Jominy).

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