

MECHANICAL AND CORROSION PERFORMANCE OF HIGH-DENSITY FERRITIC STAINLESS STEELS MANUFACTURED BY POWDER-METALLURGY

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Abstract

A new method for reducing the porosity of powder metallurgical (PM) stainless steels is their manufacturing from mixes of water atomized (*wa*) powders and gas atomised (*ga*) powders. This work presents results about the decrease on the porosity achieved using this method for PM ferritic stainless steels manufactured with *wa* 434L grade powders with additions up to 20% of *ga* 430L grade powders. The reduction of the porosity causes an improvement on the mechanical behaviour of the stainless steels. The results of the *dc* electrochemical studies carried out with these materials prove that the additions of *ga* powders do not only causes a reduction of the real surface of the PM stainless steels exposed to the corrosive attack, but also reduce the strength of the corrosion cells formed on their surface.

Introduction

Powder metallurgy (PM) offers clear advantages in the manufacturing of small-sized pieces of complicated shapes. Stainless steel powders are used for the production of parts when a high corrosion resistance and/or a certain aesthetic appearance are required. The characteristic porosity of PM stainless steels greatly affects their corrosion and mechanical behaviour. Pores promote crack initiation and propagation, thus affecting the mechanical performance of the steels [1]. Pores also favour the formation of corrosion cells [2,3] and the corrosion rate values calculated as a function of the apparent surface of the samples are highly influenced by the amount and morphology of the porosity. Hence, PM stainless steels are more prone to mechanical failure and corrosion than wrought stainless steels of the same composition [4].

Recently, PM stainless steels have been proposed for several applications at moderately high temperatures (up to 800°C), for instance: components of exhaust pipes, turbocompressors and solid oxide fuel cells. PM ferritic stainless steels have proved to have higher high-temperature oxidation resistance than PM austenitic or duplex stainless steels [5-8].

Powder mixes obtained from water atomized (*wa*) powders and gas atomized (*ga*) powders have demonstrated to be a new way of obtaining high density PM stainless steels compatible with traditional processing methods usually employed in the industry [9,10], without resorting to expensive and complex methods as metal injection moulding (MIM) that also allow to obtain high-density PM materials [11]. Results about oxidation resistance at high temperature and mechanical properties of PM ferritic stainless steels processed from mixes of *wa* and *ga* powders have been recently published [9,10]. The use of this type of powder changes the amount and distribution of the porosity. Hence, it is also interesting to study how *ga* powders addition affects

the mechanical properties and aqueous corrosion at room temperature. This paper presents results from tensile tests and *dc* electrochemical measurements that inform about that.

Experimental

Two kind of prealloyed powders, whose compositions are shown in Table 1, were used to manufacture the materials. *wa* AISI 434L and *ga* AISI 430L powders were selected (Figure 1). The former was chosen since it is the most employed PM stainless ferritic steel. The latter was employed since it the *ga* PM ferritic stainless steel more available commercially. Both powders differ in particle size and morphology: *wa* particles are bigger and have of irregular shape, and *ga* particles are smaller. The maximum particle size of the irregular *wa* particles was 150 μm , with an average particle size of 110 μm . The diameter of spherical *ga* particles was less than 22 μm , with an average particle size of 8 μm . The mix of both types of powders has allowed us to develop new materials with improved density.

Table 1. Chemical composition of the used stainless steel powders

AISI grade	Cr	Mo	Si	Mn	C	Fe
434L (<i>wa</i>)	16.73	1.09	0.80	0.21	0.01	Balance
430L (<i>ga</i>)	16.64	–	1.11	0.62	0.01	Balance

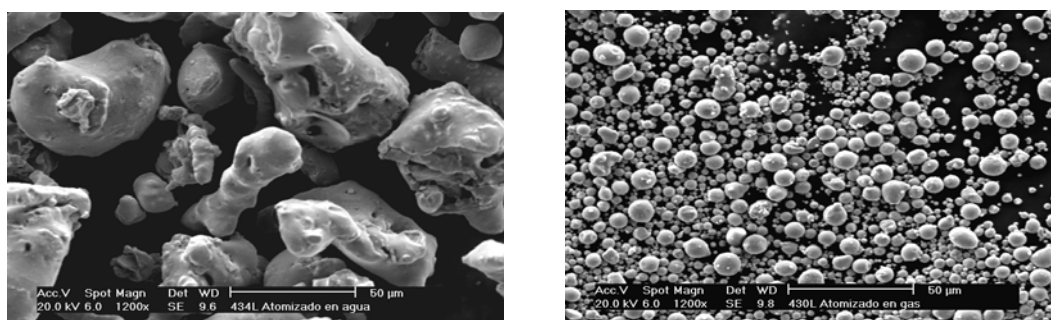


Figure 1. Scanning electronic microscopy images of the powders used: (*left*) *wa* 434L type; (*right*) *ga* 430L type.

Apart from plain 434L steel, two different mixtures were prepared with both powders, whose percentages in weight were 90% *wa* powder + 10% *ga* powder, and 80% *wa* powder + 20% *ga* powder. Mixtures richer in *ga* powders were not prepared because previous studies with other PM stainless steels have shown that the employment of larger *ga* powder amounts only produces minimum improvement in steel density [7], that is unable to balance the increase on the price of the material and the compaction difficulties.

In order to obtain mixtures with homogeneous composition, the process was carried out in several stages, adding each time greater amounts of *ga* powders to the *wa* powders. Mixing process was carried out in a ball mill employing stainless steel balls with 7.8 mm diameter. All materials were then uniaxially compacted in a single action press at 700 MPa. Pieces were manufactured with 8 g of powder using a 12.75 mm \times 31.4 mm matrix. Compacted specimens were sintered in a high vacuum furnace, reaching pressures of 10^{-4} mbar. Sintering was carried out at 1225°C during 30 min, using always heating and cooling rates of 5°C/min.

After sintering, density was measured by the water displacement procedure based on the Archimedes principle (ASTM B328). Tensile tests were performed, and the ultimate tensile strength (UTS) and the elongation of the three stainless steels were measured. The corrosion performance of the three materials was evaluated through polarization curves. In all cases, stainless steels acted as the working electrode, using their as-sintered surfaces, without any

modifications. Saturated calomel electrode (SCE) was used as reference electrode. Cyclic polarization curves have been used to test the corrosion behaviour in 0.1 M NaCl and in 0.1 M KClO₄. The sweeping rate of the potential was 0.17 mV/s.

Results and Analysis

The reduction in the porosity of the PM ferritic stainless steels achieved through the addition of *ga* powders to the traditional *wa* powders can be easily deduced from the observation of cross sectional views of the specimens as those shown in Figure 2. The reduction in the porosity is due to small-sized *ga* particles (Figure 1), that locate inside the big pores among *wa* particles, filling them. Moreover, *ga* particles have a huge amount of surface, and they enhance the diffusion phenomena among particles which sintering is based on. The porosity of the sintered materials calculated using the Archimedes method (Table 2) corroborates these observations.

The results of the tensile tests (Figure 3) show that the increases on the density (Table 2) cause an increase on the UTS and on the elongation of the steels. Not only the decrease on the global amount of the porosity, but also the change in the morphology of the pores due to *ga* powder additions (pores become smaller and rounder, as can be seen in figure 2) contributes to the improvement of the mechanical behaviour.



Figure 2. Cross sectional views of the three different PM stainless steels: (*left*) steel manufactured from 100% *wa* powder; (*centre*) steel manufactured from 90% *wa* powder + 10% *ga* powder; (*right*) steel manufactured from 80% *wa* powder + 20% *ga* powder

Table 2. Porosity volume in the studied sintered stainless steels.

PM ferritic stainless steel	100% <i>wa</i>	90% <i>wa</i> + 10% <i>ga</i>	80% <i>wa</i> + 20% <i>ga</i>
Porosity (%)	12.4	9.0	7.0

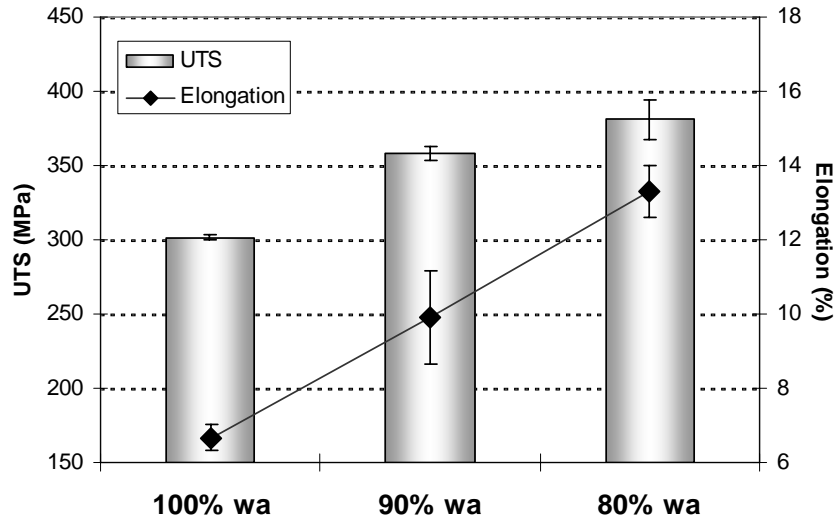


Figure 3. Results of the tensile tests carried out for three different PM stainless steels.

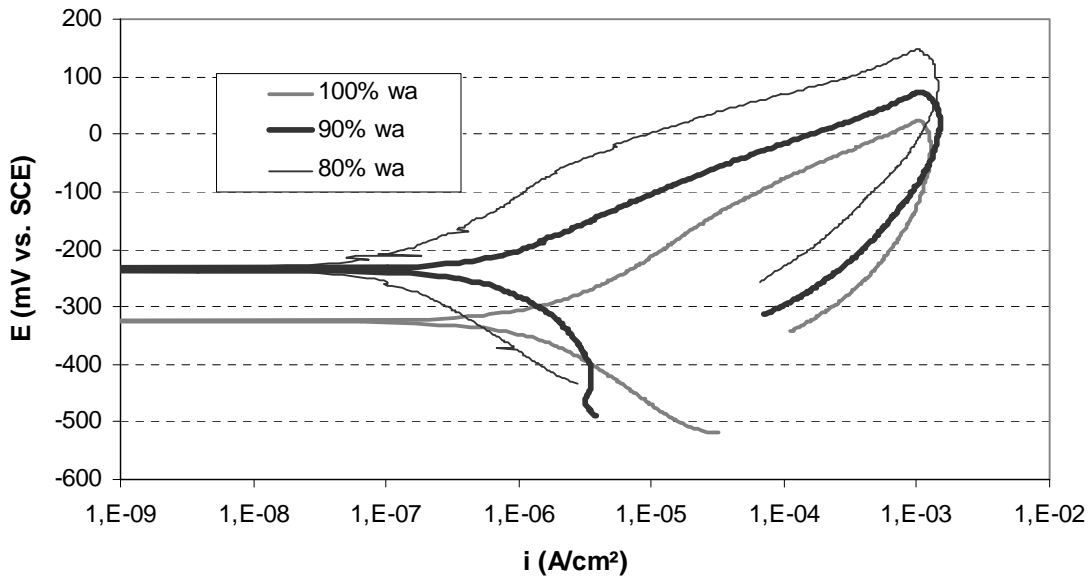


Figure 4. Polarization curves of the studied PM ferritic stainless steels in NaCl 0,1M.

The results of the polarization test carried out in NaCl solution are represented in Figure 4. The curves show a big decrease on the corrosion intensity (i_{corr}) when the amount of *ga* powders increases in the material (Table 3). The minor porosity of the material with higher *ga* powders content (Table 2) causes a decrease on the porosity of the surface of the steel, and hence, a decrease on the surface exposed to the attack during aqueous corrosion. Due to fact that the i_{corr} are calculated normalising by the apparent surface of the specimens, it is obvious that the decrease on i_{corr} are due, at least partially, to the decrease on the amount of real surface of the steels exposed to the aggressive solution during the test. However, the more homogenous morphology of the surface can also contribute to a reduction on the corrosion rate by real surface unit. Although this parameter can not be easily calculated [12], a confirmation that this phenomenon is taking place can be found in the fact that the corrosion potential (E_{corr}) tend to

become more noble as the additions of *ga* powders increases (Figure 4 and Table 3). Moreover, the visual observation of the specimens after the test (Figure 5) allows to reach to the same conclusion: the corrosion rates decrease as the percentage of *wa* powders in the stainless steels does.

Table 3. Corrosion parameters calculated from the polarization curves.

	NaCl 0,1M	
Acero	E_{corr} (mV)	i_{corr} (A/cm ²)
100% wa	-327	$1.4 \cdot 10^{-6}$
90% wa	-236	$5.1 \cdot 10^{-7}$
80% wa	-231	$1.2 \cdot 10^{-7}$

	NaCl 0.1M		KClO ₄ 0.1M	
Stainless Steel	E_{corr} (mV)	i_{Corr} (A/cm ²)	E_{corr} (mV)	i_{Corr} (A/cm ²)
100% wa	-327	$1.4 \cdot 10^{-6}$	-117	$2.7 \cdot 10^{-7}$
90% wa	-236	$5.1 \cdot 10^{-7}$	-60	$4.8 \cdot 10^{-8}$
80% wa	-231	$1.2 \cdot 10^{-7}$	4	$6.45 \cdot 10^{-9}$

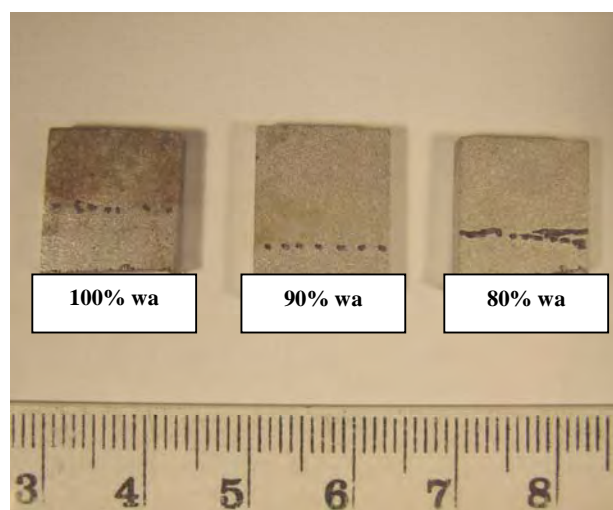


Figure 5. Visual aspect of the stainless steels after the polarization tests in figure 3.

Polarization curves carried out in media without chlorides (Figure 6) confirm the trend observed in more aggressive media. In neutral solution of KClO₄ (which is a non-corrosive electrolyte) the studied PM stainless steels do not corrode as easily as in NaCl solutions (Figure 4). In absence of chlorides, the PM stainless steels exhibit a passive region in their polarization curves of considerable length (Figure 6). As expected, the i_{corr} observed in absence of chlorides are lower than those measured in chloride medium (Table 3). The decrease on the porosity caused by the additions of *ga* powders causes a decrease on the corrosion rate due, both to the minor real surface exposed to the solution, and to the more homogeneous surface morphology, that reduces the strength of the corrosion cells formed on it. This last fact is confirmed by the clear increase detected in the E_{corr} .

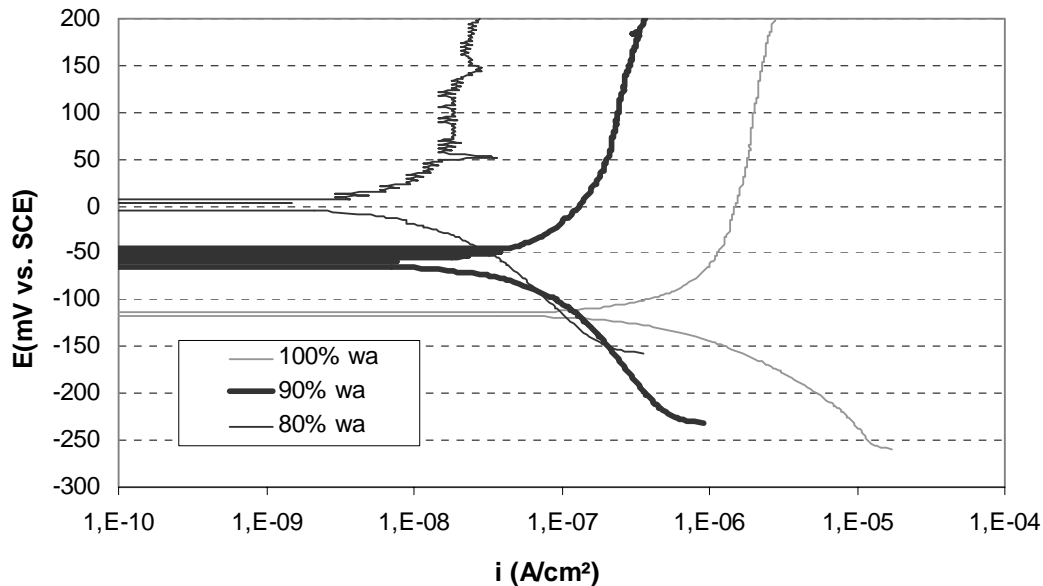


Figure 6. Polarization curves of the studied PM ferritic stainless steels in KClO_4 0.1M.

Conclusions

Additions of up to 20% of *ga* powders to *wa* powders cause the improvement on the mechanical properties of the PM ferritic stainless steels, because they reduce the global amount of porosity and make the pores to become smaller and rounder.

The decrease on the porosity of PM stainless steels achieved through the additions of *ga* powders to traditional *wa* powders does not only causes a reduction of the real surface of the materials exposed to the attack, but also reduce the strength of the corrosion cells formed on their surface. This fact has been confirmed in neutral media with chlorides and without chlorides.

Acknowledgements

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