A SIMPLIFIED MODEL FOR THE IMPACT RESISTANCE OF POROUS SINTERED STEELS

A. Molinari, C. Menapace, E. Santuliana, G. Straffelini

Abstract

In this work a simplified model for the impact resistance of porous 1.5%Cr-0.2%Mo sintered steels is proposed. Yield and maximum loads have a linear dependence on the fraction of the load bearing section \( \Phi, P_y = P_{y0} \Phi \) and \( P_{\text{max}} = P_{\text{max}0} \Phi \) where \( P_{y0} \) and \( P_{\text{max}0} \) are the corresponding properties of the metallic matrix and depend on its microhardness. Deflection and impact energy have an exponential dependence on \( \Phi \), \( \delta = a + be^{c(\Phi)} \) and \( E = a_1 + b_1 e^{c_1(\Phi)} \), where \( a, b, c, a_1, b_1 \) and \( c_1 \) are constants which depend on the matrix microstructure rather than on microhardness.

Keywords: impact properties, fraction of load bearing section

INTRODUCTION

Mechanical properties of porous sintered steels are strongly influenced by residual porosity which causes strain localization and limits the spreading of deformation away from the neck regions. This is enhanced by the high strain rate inherent in the impact tests, and consequently the effect of porosity on impact properties is larger than that on the tensile and bend.

The impact behaviour of porous sintered steels has been extensively, previously investigated by the authors by means of instrumented impact tests, to highlight the effect of green density, sintering temperature and chemical composition of the materials. Porous steels may present three different behaviours depending on the chemical composition (mainly carbon content), on the alloying method (prealloying vs. diffusion bonding) and on density: distinct yield with more or less extensive plastic strain (typical of low-medium carbon steels), continuous yield with strain hardening (typical of diffusion bonded materials) and macroscopic elastic behaviour (typical of high carbon steels with low density) [1-4]. The extension of plastic deformation before crack nucleation, as well as its occurrence in high carbon steels increases with green density and sintering temperature [3, 5-10], due to the reduction of the amount of residual porosity and to the improvement of the pore morphology, which attenuates strain localization. As far as the effect of microstructure is concerned, it has been shown that an increase in its microhardness decreases the impact energy, and there is a threshold over which the material becomes brittle [11-13]. The microhardness threshold increases with density and sintering temperature [4, 7, 9]. The sintering temperature has additional effects on the microstructure of the metallic matrix, which influence the impact behaviour:

- in the Ni diffusion bonded steels a high sintering temperature promotes Ni diffusion in the ferrous matrix, increasing its microhardness [14];
- in the Cr steels a high sintering temperature activates the reduction of chromium oxide by carbon, causing decarburization and a decrease of microhardness [6].
Finally, the crack propagation energy is negligible, apart from the case of steels with a low carbon, a high density and sintered at high temperature where the combination of a high density, a rounded pore morphology and a ductile matrix result in a measurable resistance to crack propagation [8, 9].

The influence of density and sintering temperature on the impact resistance can be rationalized by considering the load bearing section [15]. It is the actual section between the pores which bears the applied load and increases with green density and with sintering temperature, even in the case when the latter does not increase densification.

To propose an empirical model for the impact properties of porous steels the results of instrumented impact tests collected on a homogeneous population of low Cr and Mo steels with different carbon contents, compacted to different green densities and sintered both at standard (1120°C) and high (1250°C) temperature, are here presented. The carbon content ranges between 0.05% and 0.8% and the as sintered microstructures range between ferrite and pearlite-bainite.

**EXPERIMENTAL PROCEDURE**

All the materials were produced with the prealloyed 1.5%Cr-0.2%Mo powder, to which different amounts of UF-4 Kröpfmuhl graphite (from 0.05% to 0.8%) and 0.6% Kenolube lubricant were added. Unnotched Charpy bars (55x10x10 mm) were compacted to three green densities (6.8 g/cm$^3$, 7.0 g/cm$^3$ and 7.4 g/cm$^3$) and sintered at 1120°C and 1250°C. The specimens with different carbon contents were sintered in different batches and furnaces, then the microstructure is affected by the actual sintering cycles (isothermal holding time, cooling rate). The microstructural analysis was carried out at the Light Optical Microscope (LOM). The fraction of residual pores, their size and morphology were measured by Image Analysis of unetched LOM micrographs at 100x. The microstructural constituents were investigated after etching with 50% Nital - 50% Picral solution. Microhardness was measured on the metallographic specimens with the HV0.05 scale. The microstructures and microhardnesses of the materials are reported in Table 1.

<table>
<thead>
<tr>
<th>Microstructure</th>
<th>6.8 g/cm$^3$</th>
<th>7.0 g/cm$^3$</th>
<th>7.4 g/cm$^3$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1120°C</td>
<td>1250°C</td>
<td>1120°C</td>
</tr>
<tr>
<td>0.05% C</td>
<td>α</td>
<td>α</td>
<td>α</td>
</tr>
<tr>
<td></td>
<td>86.9±4.6</td>
<td>89.7±5.1</td>
<td>88.2±8.9</td>
</tr>
<tr>
<td>0.2% C</td>
<td>50 α / 50 P</td>
<td>50 α / 50 P</td>
<td>50 α / 50 P</td>
</tr>
<tr>
<td></td>
<td>50 α / 50 P</td>
<td>50 α / 50 P</td>
<td>50 α / 50 P</td>
</tr>
<tr>
<td></td>
<td>118.2±15.4</td>
<td>131.3±21.2</td>
<td>124.3±19.4</td>
</tr>
<tr>
<td>0.3% C</td>
<td>20 α / 80 P</td>
<td>B</td>
<td>20 α / 80 P</td>
</tr>
<tr>
<td></td>
<td>217.3±12.0</td>
<td>219.8±28.6</td>
<td>320.4±16.5</td>
</tr>
<tr>
<td>0.4% C</td>
<td>20 P / 80 B</td>
<td>20 P / 80 B</td>
<td>20 P / 80 B</td>
</tr>
<tr>
<td></td>
<td>247.7±33.2</td>
<td>271.0±16.3</td>
<td>272.5±26.9</td>
</tr>
<tr>
<td>0.5% C</td>
<td>20 P / 80 B</td>
<td>20 P / 80 B</td>
<td>20 P / 80 B</td>
</tr>
<tr>
<td></td>
<td>323.4±28.4</td>
<td>355.5±43.1</td>
<td>337.4±35.2</td>
</tr>
<tr>
<td>0.8% C</td>
<td>P</td>
<td>P</td>
<td>P</td>
</tr>
<tr>
<td></td>
<td>409.2±31.2</td>
<td>412.4±30.6</td>
<td>404.8±16.8</td>
</tr>
</tbody>
</table>

Impact tests were carried out with an instrumented Charpy pendulum, recording the load-deflection curve. Available energy was 150 J and impact velocity was 3.90 m/s.
Three specimens were tested each experimental point. All the parameters characteristic of the impact behaviour: yield load $P_y$, maximum load $P_{\text{max}}$, deflection $\delta$ and total adsorbed energy $E$, were collected and averaged.

**THE IMPACT BEHAVIOUR**

Figures 1 to 3 show examples of load/deflection curves to highlight the effect of the carbon content, green density and sintering temperature. Green density is chosen rather than sintered density since it depends on the compaction methodology (cold/warm) and pressure, which are the process variables with the prevailing influence on the amount of residual pores. Sintering in the conventional temperature ranges (1120-1250°C) has a slight effect on density but, at the same time, it may greatly modify the pore morphology and the neck size, with a resulting effect on impact properties much more important than that provided by the slight increase in density.

The increase in the carbon content from 0.05% to 0.5% with constant green density and sintering temperature (Fig.1) increases the yield load and the maximum load and decreases deflection noticeably. The impact behaviour of the 0.05% C steel is characterized by a distinct yield point followed by an extensive plastic strain, whilst that of the 0.5% C shows a continuous yielding with a negligible strain hardening step. Impact energy decreases from 69 to 20 J. This effect is due to the different microstructure: ferrite in the 0.05%C steel, pearlite and bainite in the 0.5% C steel.

![Fig.1. Effect of the carbon content on the impact curve of the Cr-Mo steel.](image)

The increase in the green density from 7.0 g/cm$^3$ to 7.4 g/cm$^3$ at constant carbon content and sintering temperature (Fig.2) increases yield load, maximum load and deflection. Strength and plasticity are enhanced by densification and impact energy increases from 39 up to 103 J.

The increase in the sintering temperature at constant carbon content and green density (Fig.3) increases deflection, whilst yield load and maximum load do not change appreciably. The impact energy increases from 39 up to 69 J, even if density is not significantly increased by the increased sintering temperature.
Fig. 2. Effect of green density on the impact curve of the Cr-Mo steel.

Fig. 3. The effect of sintering temperature on the impact curve of the Cr-Mo steel.

Whilst the effect of the carbon content is ascribed to the change in the microstructure and that of green density is obviously due to the as-sintered density, the effect of the sintering temperature is mostly due to the increase in the neck size which occurs on sintering at 1250°C, even if density does not increase significantly.

THE FRACTION OF THE LOAD BEARING SECTION

As is well known, the load bearing section \( A_r \) is lower than the nominal cross section \( A_n \) because of the localization of deformation and fracture in the neck regions. The fraction of the load bearing section \( \Phi \) is then lower than \( 1-\varepsilon \), where \( \varepsilon \) is the fractional porosity. Different equations were proposed to calculate \( \Phi \) from porosity [16, 17] and from the elastic modulus [18]. Danninger et al. proposed a method to obtain \( \Phi \) by measuring the extension of the fractured areas on the fatigue or low temperature impact fracture surfaces [15, 19] . Straffelini and Molinari [20] developed an empirical method to determine the fraction of the load bearing section from the metallographic analysis. Since the increase in the neck size due to high temperature sintering is accomplished by an improvement of the pore morphology, they elaborated a method to calculate \( \Phi \) from the fractional porosity and the morphological parameter \( f_{\text{circle}} \) determined by quantitative metallography, using equations (1) and (2)

\[
\Phi = [1 - (5.58-5.7 f_{\text{circle}}) \varepsilon]^2
\]

\[
f_{\text{circle}} = 4 \pi A / P^2
\]
where A and P are the area and the perimeter of the pores in the metallographic image, respectively. As an example, Fig. 4 shows the effect of sintering temperature on the distribution of $f_{\text{circle}}$ in the 0.8% C steel.

![Fig. 4. The influence of the sintering temperature on the distribution of $f_{\text{circle}}$.](image.png)

Figure 5 shows, as an example, the fraction of the load bearing section of the 0.05% C steel versus porosity at the two sintering temperatures. The influence of the sintering temperature is noticeable and increases on increasing the fractional porosity.

![Fig. 5. The fraction of the load bearing section as a function of porosity and sintering temperature.](image.png)

**THE SIMPLIFIED MODEL**

Figure 6 shows, as an example, the influence of $\Phi$ on yield load (a), maximum load (b), deflection at fracture (c) and impact energy (d) for the 0.05% C steel. Both yield and maximum load are correlated to the fraction of the load bearing section by a linear relation, similarly to the corresponding parameters of tensile tests in the case of materials.
with an elasto-plastic behaviour [12]. The correlations can be expressed by the following equations

\[ P_y = P_{y0} \Phi \]  
(1)
\[ P_{\text{max}} = P_{\text{max0}} \Phi \]  
(2)

where \( P_{y0} \) and \( P_{\text{max0}} \) are the yield load and the maximum load of the matrix, respectively. The same correlations were found for all the other steels considered.

The effect of \( \Phi \) on deflection is different, since it results progressively, enhanced by increasing the fraction of the load bearing section. This is due to the progressive attenuation of the localization of deformation in the neck areas, which results in an ever increasing volume of the metallic matrix involved in plastic deformation. The best fit of experimental data is provided by equation (3)

\[ \delta = a + be^{\phi\Phi} \]  
(3)

where \( a, b \) and \( c \) are constants. Deflection is a measure of ductility during impact loading. In tensile tests, ductility is represented by percent elongation at fracture, which is correlated to the fraction of the load bearing section as \( \varepsilon = \varepsilon_0 \Phi^{3/2} \), where \( \varepsilon_0 \) is the tensile elongation of the matrix [21]. The same model does not fit deflection data, probably because of the different loading conditions during impact test (tensile loading on one side, compressive loading on the other one). Equation (3) is simply the mathematical model, since a physical explanation has not yet been proposed. However, its validity is confirmed by deflection

![Graphs showing yield load, maximum load, deflection, and impact energy vs. fraction of load bearing section for 0.05% C steels.](image)
data of all the other steels here considered. The effect of the fraction of the load bearing section on impact energy is very similar to that on deflection, confirming that impact energy is more closely correlated to ductility than to strength. The following equation is proposed:

\[ E = a_1 + b_1 e^{c_1 \Phi} \]  

where \( a_1, b_1 \) and \( c_1 \) are constants.

The individual correlations for all the materials are reported in Fig. 7. The graph relevant to yield load highlights a clear correlation with microhardness. The quality of the linear fit is acceptable in relation to the uncertainty in the determination of \( P_y \) from the impact curves. On increasing microhardness at the same fraction of the load bearing section, \( P_y \) increases, as it was expected. The experimental data can be grouped into three classes: 80-150 HV 0.05; 200-280 HV 0.05; 320-400 HV 0.05, differing for the value of \( P_{y0} \) which increases with microhardness. The same trend is shown by \( P_{\text{max}} \), even if the quality of the fit is lower than in the previous case. \( P_{\text{max}} \) does not depend only on microhardness; it depends on ductility and on strain hardening of the material, too. This justifies the lower accuracy of the model proposed. However, in a first attempt to correlate impact properties to the fraction of load bearing section and to the properties of the metallic matrix, the same approach used for yield load was used, dividing the experimental points into the same three microhardness classes.

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**Fig. 7.** Yield load (a), maximum load (b), deflection (c) and impact energy (d) vs. the fraction of the load bearing section for all the investigated steels.

Deflection and impact energy depict a different trend, since in both cases microstructure is selective rather than microhardness. The figures show that the
experimental data can be grouped into three classes: ferrite; ferrite-pearlite; pearlite and pearlite-bainite, which are characterized by a different ductility. At constant fraction of the load bearing section, both deflection and impact energy decrease on decreasing the matrix ductility.

Table 2 and 3 reports the parameters and the constants of the models proposed.

Tab.2. Parameters of the models proposed for yield load and maximum load.

<table>
<thead>
<tr>
<th>HV0.05</th>
<th>Yield load</th>
<th>Maximum load</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$P_{y0}$ [kN]</td>
<td>$P_{max0}$ [kN]</td>
</tr>
<tr>
<td>80-150</td>
<td>13.49</td>
<td>19.21</td>
</tr>
<tr>
<td>200-280</td>
<td>16.13</td>
<td>25.14</td>
</tr>
<tr>
<td>320-400</td>
<td>20.23</td>
<td>31.60</td>
</tr>
</tbody>
</table>

Tab.3. Constants of the models proposed for deflection and impact energy.

<table>
<thead>
<tr>
<th>Matrix</th>
<th>Deflection</th>
<th>Impact energy</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>a</td>
<td>b</td>
</tr>
<tr>
<td>ferrite</td>
<td>2.97</td>
<td>0.0007</td>
</tr>
<tr>
<td>ferrite-pearlite</td>
<td>1.30</td>
<td>0.0195</td>
</tr>
<tr>
<td>Pearlite-bainite</td>
<td>1.11</td>
<td>0.0001</td>
</tr>
</tbody>
</table>

CONCLUSIONS

The impact resistance of porous sintered steels depends on green density, sintering temperature and microstructure of the metallic matrix. Green density and sintering temperature influence the amount of the residual porosity, the neck size and the pore morphology. These three factors contribute to the definition of the fraction of the load bearing section. In this work, the impact properties of several 1.5% Cr - 0.2% Mo steels, containing different carbon contents, compacted to different green densities and sintered at conventional and high temperature were measured and correlated to the fraction of the load bearing section and to the properties of the metallic matrix. Tests were carried out by means of an instrumented Charpy apparatus, to measure the characteristic parameters of the impact behavior: yield load $P_y$, maximum load $P_{max}$, deflection $\delta$ and impact energy $E$. The fraction of the load bearing section $\Phi$ was calculated from the fractional porosity and the $f_{circle}$ parameter, representative of pore morphology.

Yield and maximum load have linear dependences on $\Phi$, $P_y = P_{y0}\Phi$ and $P_{max} = P_{max0}\Phi$ where $P_{y0}$ and $P_{max0}$ are the corresponding properties of the metallic matrix and depend on its microhardness. Deflection and impact energy have an exponential dependence on $\Phi$, $\delta = a + be^{(c\Phi)}$ and $E = a_1 + b_1e^{(c_1\Phi)}$, where $a$, $b$, $c$, $a_1$, $b_1$ and $c_1$ are constants which depend on the matrix microstructure rather than on microhardness.

The correlations proposed need further investigation, with the support of a larger number of experimental points. However, they are definitely reasonable. On increasing the fraction of the load bearing section, impact strength ($P_y$ and $P_{max}$) increase linearly, whilst impact ductility (deflection) and energy increase much more, since they depend on the volume of the matrix which is involved in plastic deformation. Moreover, impact strength is influenced by the microhardness of the metallic matrix, whilst impact ductility, and consequently impact energy, are influenced by its ductility. A physical model for deflection has to be developed, since that proposed for tensile elongation does not work.
The model is based on the characteristic parameters of the impact curve obtained by Charpy tests on 55x10x10 mm specimens, and it is rigorously applicable to this specific loading condition. It can be therefore used to predict the unnotched Charpy impact strength of porous steels produced by prealloyed powders.

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REFERENCES