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Dynamic and quasi-static compression of porous carbon steel S30C and S45C with directional pores

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ABSTRACT

Dynamic and quasi-static compressive deformation of as-cast and normalized porous S30C and S45C carbon steels with unidirectional cylindrical pores was investigated to evaluate the effect of matrix brittleness on the appearance of a plateau stress region where deformation proceeds with almost no stress increase. Dynamic compression tests were carried out at room (298 K) and cryogenic (77 K) temperatures using the split Hopkinson pressure bar method, and quasi-static compression tests were carried out at room temperature using universal testing machine. Compression perpendicular to the orientation of the pores does not generate a plateau stress region, regardless of the matrix brittleness, which depends on the strain rate, temperature, carbon content, and heat-treatment conditions. Localized deformation and crack formation originating from a high concentration of stress around the pores during perpendicular compression promote densification in the early stage of the stress–strain curves, thereby precluding the appearance of the plateau stress region. On the other hand, a plateau stress region appears during compression parallel to the orientation of the pores. The appearance of the plateau stress region is, however, limited when rapid crack propagation and large work hardening are suppressed by the ductility of the matrix and the formation of deformation bands, which originate from the intermediate brittleness of the matrix metal and anisotropic pores. The appearance of the plateau stress region confers a high-energy absorption capacity on the as-cast porous carbon steel S45C, with an absorbed energy value of $86.8 \pm 1.6\,\mathrm{kJ\,kg^{-1}}$, which is ten times higher than that of aluminum foams with isotropic pores. The energy absorption efficiency reaches $85.9 \pm 6.8\%$, which is almost the same as that of the aluminum foams.

1. Introduction

Porous metals exhibit superior characteristics such as sound and impact energy absorption; these characteristics coupled with their light weight have resulted in these metals being attractive materials for use in various engineering fields [1–5]. The impact energy absorption characteristics have garnered particular interest because this property is highly advantageous for applications in the automobile and railway industries. Consequently, significant resources have been devoted to the research of the compressive properties and energy absorption characteristics of porous metals, with a particular focus on closed-cell and open-cell aluminum foams with a porosity over ∼80% [6–11].

In the dynamic compressive deformation of porous metals, the impact energy is absorbed in a plateau stress region where deformation proceeds with almost no stress increase [2,5]. During compressive deformation of aluminum foams with spherical or isotropic pores, a plateau stress region appears as a result of sequential formation of deformation bands, originating from the high porosity and inhomogeneous pore morphology of the foams [5]. Given that the low plateau stress caused by the high porosity and concentration of stress around pores results in the low absorbed energy, further extension of the plateau stress region and enhancement of the energy absorption capacity of the foams are desirable features for improved material performance, and various studies have been carried out toward this end.

Recently, Tane et al. [12–14] investigated the dynamic compression of porous metals with unidirectional cylindrical pores, referred to as lotus-type porous metals [3,4] or GASAR metals [15]. These studies revealed that the dynamic compression of porous carbon steel S15CK in the pore direction (parallel to the orientation of pores) produces a stress–strain curve that exhibits a plateau stress region with a high stress amplitude and wide strain region despite its low porosity of ∼50%, and thus, the absorbed energy is much higher than that of aluminum foams. Nonetheless, in that instance, the appearance of the plateau stress region was limited to the dynamic compression at low temperature (77 K). To realize practical applications of impact energy absorption, materials that exhibit the appearance of the plateau stress region at room

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Table 1
Chemical compositions of S30C and S45C carbon steel in mass% unit.

Materials	Fe	C	Si	Mn	P	S	Cu	Ni
S30C	Bal.	0.33	0.21	0.68	0.018	0.013	0.02	0.03
S45C	Bal.	0.44	0.2	0.71	0. 01	0.015	0.12	0.059

temperature are required. Previous studies [13,14] have revealed a correlation between the appearance of the plateau stress region and the brittleness of the matrix metal. Thus, to achieve judicious control of the appearance of the plateau stress region during dynamic compression at room temperature, the effect of matrix brittleness on the dynamic compression of porous metals with oriented pores must be clarified.

In the present study, the dynamic compression of as-cast and normalized porous carbon steels, S30C and S45C, with unidirectional cylindrical pores is investigated at room (298 K) and cryogenic (77 K) temperatures using the split Hopkinson pressure bar (SHPB) method to clarify the effect of matrix brittleness on the appearance of the plateau stress region. The effect of the strain rate on the matrix brittleness and compressive deformation was also evaluated by quasi-static compression performed at room temperature. The deformation modes that generate the appearance of the plateau stress region are clarified via scanning electron microscope (SEM) observation of the porous structures after compression.

2. Experimental procedure

S30C and S45C carbon steel rods, which correspond to AISI 1030 and 1045, respectively, were used as raw materials. The chemical compositions of the rods are listed in Table 1. Porous S30C and S45C ingots with cylindrical pores oriented in the solidification direction were prepared by a continuous zone melting technique [16] in which the raw S30C and S45C rods were continuously melted and unidirectionally solidified in a hydrogen atmosphere using a transfer velocity of 330 μm s^{-1}, which corresponds to the solidification rate, and a hydrogen gas pressure of 2.5 MPa. These specimens are referred to hereafter as as-cast porous specimens.

Cylindrical specimens for dynamic and quasi-static compression tests were cut from the as-cast porous S30C and S45C ingots using a spark erosion cutting machine (AQ325L, Sodick Corp., Yokohama, Japan). The diameter and height of the specimens was 6 mm, where the height direction was either parallel or perpendicular to the orientation of the pores. Specimens 3 mm in height were also prepared to obtain the stress–strain curves up to a high-strain region in the dynamic compression [12].

About half of the as-cast porous S30C specimens were subjected to a normalizing heat treatment consisting of austenitization at 1173 K for 3.6 ks and cooling at room temperature. Similarly, about half of the as-cast porous S45C specimens were subjected to a normalizing heat treatment consisting of austenitization at 1163 K for 3.6 ks and cooling at room temperature. The porosity of the as-cast and normalized specimens was evaluated on the basis of relative density. The diameter of the pores in a cross section perpendicular to the pore direction was measured using an image analyzer (Win-Roof, Mitani Corp., Fukui, Japan).

Dynamic compression tests were carried out at 77 and 298 K using the SHPB method [12,17], where the strain rate was $(3.5 \pm 0.5) \times 10^3$ s^{-1}. For the compression at 77 K, the specimens were compressed in a chamber filled with liquid nitrogen. For comparison, quasi-static compression tests were carried out at 298 K using a universal testing machine (Model 5582, Instron Corp., Canton, MA, USA), where the strain rate was 2.8×10^{-3} s^{-1}.

As-cast and normalized porous specimens were etched with nital solution, and the microstructures in the matrix region of each specimen were observed using an optical microscope (Optiphot, Nikon Co. Ltd., Tokyo, Japan). The porous structures were observed before and after 20% compression using an SEM (JSM-6300T, JEOL Corp., Tokyo, Japan) or the optical microscope.

The absorbed energy per unit mass, W, was calculated from the compressive stress-strain curves using the following equation:

$$W = \frac{\int_0^{\varepsilon_{0.5}} \sigma \, d\varepsilon}{\rho}, \quad (1)$$

where ρ is the density of the porous carbon steel and $\varepsilon_{0.5}$ is a nominal strain of 50%. The efficiency of absorbed energy, η, was calculated using the following equation:

$$\eta = \frac{\int_0^{\varepsilon_{0.5}} \sigma \, d\varepsilon}{\sigma_{0.5} \cdot \varepsilon_{0.5}}, \quad (2)$$

where $\sigma_{0.5}$ is the nominal stress value at 50% strain. The calculated absorbed energy per unit mass and efficiency of absorbed energy were compared with those of metal foams [8–14,18,19].

3. Results

3.1. Pore morphology and microstructure of porous S30C and S45C

Fig. 1 shows the SEM images of the (a) side and (b) top surfaces of a cylindrical as-cast porous S30C specimen, where the height direction is parallel to the pore direction. Some small pores with low aspect ratios are dispersed between larger pores as shown in the side surface view. The measured average pore diameter and porosity are 685 ± 301 μm and 46.5%, respectively. The SEM images of the side and top surfaces of an as-cast S45C specimen are shown in Fig. 1(c) and (d), respectively. The pore morphology is inhomogeneous compared with that of the S30C sample, and thus, many structural weak points where stress may concentrate during compression are present. This is possibly due to the increase in the freezing interval (which is the range of temperatures between solidus and liquidus lines) with an increase in carbon content, which leads to an increase in the mushy zone width and thus suppresses pore formation and growth [3]. The average pore diameter and porosity of as-cast porous S45C are 647 ± 271 μm and 43.4%, respectively, which are comparable to those of the S30C sample.

Fig. 2(a) shows the microstructure in the matrix region of as-cast porous S30C. The microstructure consists of the Widmanstätten ferrite and eutectoid pearlite phases. The normalizing heat treatment induces a change in the as-cast microstructure into the fine microstructure consisting of ferrite and pearlite phases, as shown in Fig. 2(b). In contrast to the microstructure of as-cast porous S30C, the microstructure of as-cast porous S45C consists of bainite, pearlite, and martensite phases, as shown in Fig. 2(c). Normalizing heat treatment changes the as-cast microstructure of as-cast porous S45C into the fine microstructure consisting of ferrite and pearlite phases (Fig. 2(d)), similar to the behavior of porous S30C.

3.2. Stress–strain curves

3.2.1. Compression perpendicular to the pore direction

Fig. 3(a) shows the nominal stress–nominal strain curves of as-cast porous S30C and S45C under quasi-static compression perpendicular (⊥) to the pore direction ("perpendicular compression") at 298 K. The data points and error bars denote the average flow stress and standard deviations for four specimens, respectively. The flow stress of as-cast porous S30C increases monotonically with an increase in strain, whereas there is a drop in the flow stress of S45C between 5% and 10% strain. Above ~30% strain, the flow stress of as-cast porous S30C and S45C increases steeply with increasing