An experimental study of the deformation rate sensitivity of PM aluminium foams

H.Zhao[+], **S. Abdennadher**[+] and **J.Banhart***
[+]Laboratoire de Mécanique et Technologie, ENS-Cachan/CNRS/University Paris 6
61, Avenue du président Wilson, 94235 Cachan cedex, France
*Hahn-Meitner-Institut Berlin (HMI), Glienicker Str. 100, 14109 Berlin, Germany

This paper presents an experimental study using a new testing device based on a nylon Hopkinson bar system with 60 mm diameter, which provides a solution for both the impedance match and the problem of reasonable specimen size when testing metal foams. PM aluminium foams cylinders with closed outer skins (45 mm diameter and 60 mm length) were tested in both the standard SHPB configuration (specimen between two nylon bars), and the block bar configuration (specimen in front of input bar) to obtain a higher loading rate. Despite unavoidable scatter for this kind of materials, the slight rate sensitivity could be observed. In addition, tests with strain rate jumps on the same specimen were carried out (static loading after a dynamic loading or dynamic loading after static one). A discontinuity of stress-strain curve is found for the two cases. This gives another proof that this foam is rate sensitive in this range of loading rate.

1 Introduction

Aluminium foams nowadays attract a lot of attention. A large number of experimental, numerical, and analytical studies have been reported in the literature [1,2]. Most previous work deals with various problems under quasi-static loading. However, one of the main applications of aluminium foams is to absorb energy in crash situations, e.g. in accidents. The rate sensitivity of the properties of such aluminium foams is then a key point in the engineering design for energy absorbers and accurate experimental information is needed.

Under impact loading the behaviour of cellular materials has been mostly studied using a SHPB (Split Hopkinson Pressure Bar) or similar techniques. Deshpande and Fleck [3] used a standard SHPB arrangement (diameter 12.7 mm) with a polymer output bar to study closed-cell “Alulight” and open-cell “Duocel” aluminium foams. Results are found with a pronounced scatter partially because of the small size of specimens. They suggest no rate sensitivity. Mukai et al. [4] has used a standard SHPB arrangement for closed-cell “Alporas” aluminium foams. Their results show some rate sensitivity. Tan et al. [5] reported impact tests using a gas-gun to launch a closed-cell “Hydro-Cymat” aluminium alloy foam projectile. They use a Hopkinson bar to measure the crushing pressure and propose a shock-wave theory to explain the observed pronounced rate sensitivity in their tests. Testing under impact loading of metallic foams has two major difficulties. One is the low strength of foams which, however, can be overcome by using a compliant polymer bar. Another problem is the large scatter of results due to the small specimen size in relation to cell size.

Common SHPB measurements using small diameter (≈10 mm) steel bars do not provide satisfactory results for metal foams. They give rise to problems such as weak signals due to the impedance difference and the lack of representativity due to small specimen sizes comparable with the cell size. In this paper a 60 mm diameter Nylon

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SHPB arrangement is used to improve the measuring accuracy. PM aluminium foams with closed outer skins are studied in static tests, standard SHPB tests, direct impact tests and also rate jump tests.

2 Al6061 foam specimen and standard static compression

Foam samples were manufactured in a two-stage process. First, precursor materials were made from pre-alloyed AA6061 powder and 0.5 wt.% TiH_2 powder acting as a blowing agent by consolidation via cold isostatic pressing followed by hot extrusion to long rectangular rods. The second step - foaming of the precursors associated with gas generation - was carried out in a batch furnace with indirect conductive heating and air circulation at 730°C. The process is described in detail in the literature [1].

The manufactured foam specimens are cylinders of 45 mm diameter and 60 mm height with closed outer skins. As one of the advantages of the PM foaming process is the option to make final products (shaped parts or sandwich plates) directly without any machining, this skin will mostly exist in final products. It therefore makes sense to test the PM foam with his skin. The densities of the entire specimens are about 620±20 kg/m^3. X-ray tomograpic images reveal that the foam is not really homogeneous and quite large cavities can be found inside the specimen. Such CT images permit one to select a group of less heterogeneous specimens to perform this study but experimental results still show scatter.

Static tests are performed using a universal testing machine. The strain range can be limited to about 20% because our interest is mainly focused on the mean plastic flow stress which can be determined from the initial deformation range. This also allows us to make rate jump tests. The measured mean stress level and scatters are comparable with results of a previous study of the same foam specimens [6]. Some foams have nearly no strain hardening while others present a weak hardening effect.

3 Impact test using a large diameter nylon SHPB system

3.1 General SHPB theory

The SHPB (Split Hopkinson Pressure Bar), also called the Kolsky apparatus, is a commonly used experimental technique to study constitutive laws of materials at high strain rates [7,8]. A typical SHPB shown in Fig. 1 is composed of the long input and output bars with a short specimen placed between them. The impact between the projectile and the input bar creates a compressive longitudinal incident pulse $\varepsilon_i(t)$ in the input bar. Once this incident pulse reaches the specimen-bar interface a reflected pulse $\varepsilon_r(t)$ in the input bar and a transmitted pulse $\varepsilon_t(t)$ in the output bar are developed. With strain gauges cemented to the input and output bars one can record these three pulses and determine the forces and particle velocities at both faces of the specimen.

Conventional analysis is based on the mechanics of the elastic wave propagation in bars. The transmitted wave can be shifted to the output bar-specimen interface to obtain the output force and velocity, whereas the input force and velocity can be determined via the incident and reflected waves shifted to the interface input bar/specimen. The forces and the velocities at both faces of the specimen are then given by the following equations (1)

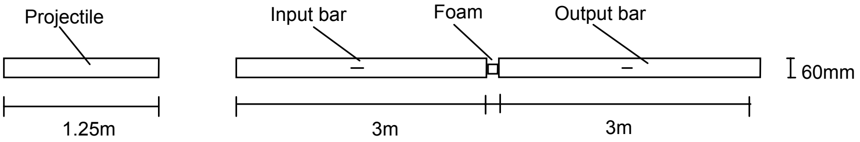

Fig. 1. Split Hopkinson pressure bar set-up

$$
\begin{aligned}
F_{input}(t) &= S_B E(\varepsilon_i(t) + \varepsilon_r(t)) \qquad & V_{input}(t) &= C_0(\varepsilon_i(t) - \varepsilon_r(t)) \\
F_{output}(t) &= S_B E \varepsilon_t(t) \qquad & V_{output}(t) &= C_0 \varepsilon_t(t)
\end{aligned} \tag{1}
$$

where $F_{input}, F_{output}, V_{input}, V_{output}$ are forces and particle velocities at the interfaces, S_B, E and C_0 are respectively the cross section of the bars, Young's modulus, the longitudinal wave speed, and $\varepsilon_i(t), \varepsilon_r(t), \varepsilon_t(t)$ are the elastic waves within the bars at the bar-specimen interface.

From forces and velocities at both bar-specimen interfaces classical analysis assumes the axial uniformity of stress and strain fields in the specimen and an average stress strain curve can be obtained (like those for a quasi-static test) which leads to the so-called two-wave analysis.

$$
\dot{\varepsilon}_s(t) = \frac{V_{output}(t) - V_{input}(t)}{l_s} \quad \text{and} \quad \sigma_s(t) = \frac{F_{output}(t)}{S_s} \tag{2}
$$

To test the PM aluminium foam a large diameter (60 mm) nylon SHPB was built and used. As the basic observable of a SHPB system is the strain profile associated with waves propagating in bars they should be accurately measured. Let us consider the transmitted wave $\varepsilon_t(t)$ as an example. One can see that the transmitted wave is just proportional to the force to be measured at the bar-specimen interface and the coefficient of this proportionality is the cross-sectional area and Young's modulus of the bar. The main characteristic of foams is their weak resistance with respect to a solid material so that the force to be measured is small. Such small forces yield very low strains in the output bar if the usual steel bars are used. Use of soft nylon bars allows for an improvement by about 60 times the SNR. Another point is the use of a large diameter bar. In practice it is difficult to make a very small specimen of materials like foams and the specimen must be large enough to represent the material. However, the soft nylon bar is visco-elastic and wave dispersion increases steeply with the diameter of the bars. The correction of wave dispersion due to viscoelastic behaviour coupled with geometrical effects is indispensable. Indeed, a dispersion correction has been proposed [9] on the basis of the Pochhammer's and Chree's longitudinal wave solution for an infinite cylindrical elastic bar, extended to the viscoelastic bar. Even though the Pochhammer-Chree solution is not exact for a finite bar, it is easily applicable and sufficiently accurate for long bars. Such an approach for the wave dispersion correction is then accepted and applied by many authors [10]. A summary of the recent development of the SHPB or derived techniques can be found in [11].

The impact velocity for a SHPB setup is limited by the yield stress of thebar. For the nylon bar it would be damaging to strike over 20 m/s. In order to know the behaviour at higher velocities a modified Hopkinson bar set-up should be used. A simple solution is to put the specimen to the front of the input bar (Fig. 2) to protect the bars from a direct impact of the projectile [12].

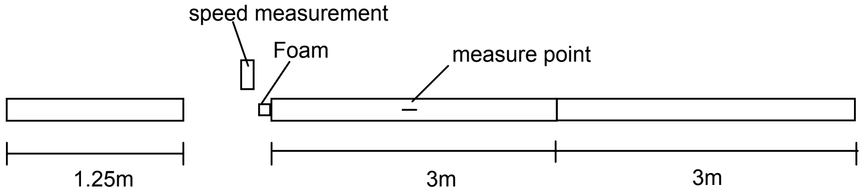

Fig. 2. A Modified SHPB setup, block bar

It is also notable that the specimen is glued to the end of input bar in our test. An eventual shock wave [13] due to an impact would propagate from the projectile side to the input bar. This means that the input bar will not measure the strength enhancement due to this shock wave.

3.2 Experimental results

Fig. 3 illustrates typical stress-strain curves under impact loading. Fig. 4 shows the flow stress at 10% of nominal strain with respect to the logarithmical value of the nominal strain rate. It shows an enhancement of only 15% in the mean flow stress. However, the scatter is quite important and the lowest value under impact loading is nearly the same as the highest value under static loading.

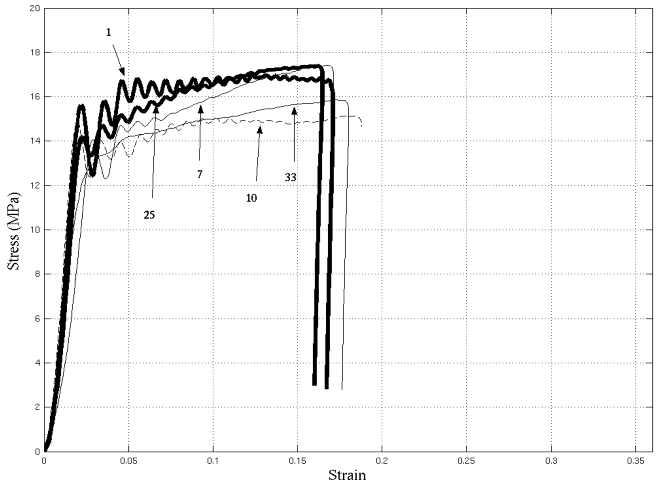

Fig. 3. Stress-strain curves after impact

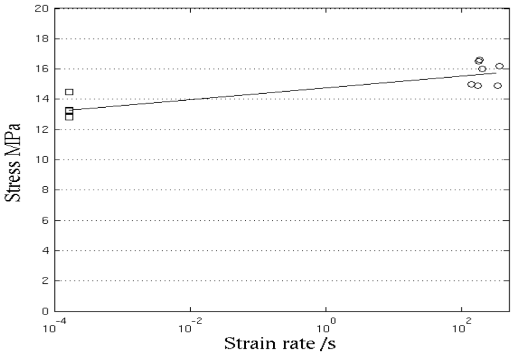

Fig. 4. Strain rate sensitivity of foam compression.

In order to eliminate the uncertainty of the rate sensitivity caused by the scatter due to the specimens morphological and mass dispersion one can attempt to carry out static and dynamic tests on the same specimen. This will be possible for specimens showing no strain hardening effect. Two combinations of loading are carried out on two non-hardening and two strain hardening specimens: the first is a static loading to a given stain followed by the crushing under impact loading (Fig. 5); another is an inversed dynamic-static test (Fig. 6).

4 Conclusions

In this paper, the mechanical behaviour of PM aluminium foam specimens with a closed outer skin is studied under static and dynamic loading. A 60 mm diameter nylon SHPB system is developed to overcome testing difficulties under impact loading such as the weak strength of foams and the large cell size. Standard SHPB tests and direct impact tests are performed and significant rate sensitivities are observed. To eliminate the uncertainty due to suspected specimen disparities, rate jump tests on the same specimen are also carried out and lead to the same rate sensitivity.

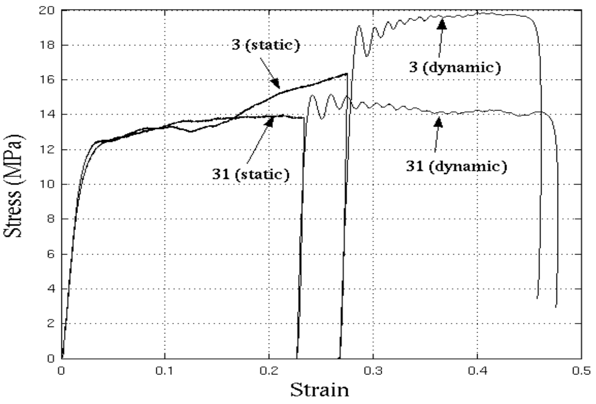

Fig. 5. Static-dynamic rate jump test

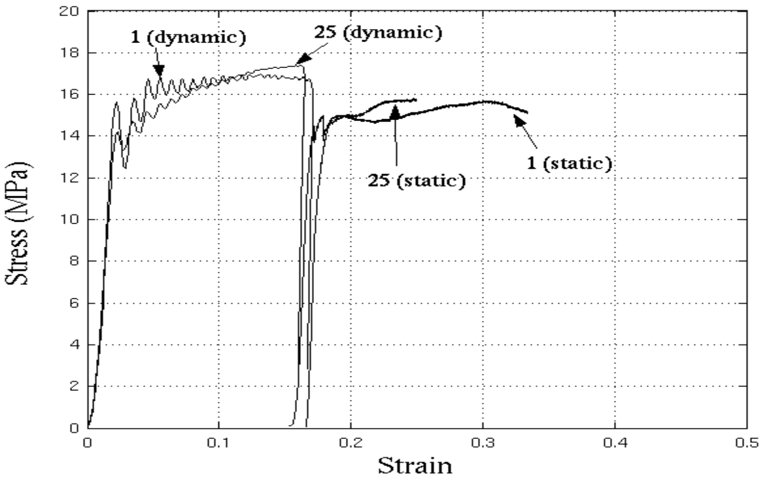

Fig. 6. Dynamic-static rate jump test

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