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Impact response of high density flexible polyurethane foam

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ABSTRACT

The impact response of high density flexible polyurethane-based foam was studied in a series of symmetric (both the impactor and the sample made of the same foam) planar impact experiments, with continuous VISAR monitoring of the velocity of the rear sample surface. The impact velocities in these experiments varied from 43 to 605 m/s providing a sample compression over the 0.36–51-MPa pressure range, with the strain rates changing, respectively, from 4×10^3 to 6×10^5 s^{-1}. The linear shock velocity-particle velocity Hugomiot of the foam, $U_S = U_{S0} + su = 14.8 + 1.318u$, was determined on the basis of the recorded velocity histories. The rise times of the velocity histories allows one to conclude that under shock compression above 3.2 MPa, the initial structure of the foam is completely crushed and the foam resistance to the propagation of the shock is determined by the void-free foam material. The dynamic tensile (spall) strength of the foam, determined in a separate impact experiment with 1-mm thick foam impactor was found equal to 0.3 MPa. Such unexpectedly low spall strength is possibly the result of substantial damage having taken place in the foam during compression.

1. Introduction

The ability of polymeric foams to absorb energy of impact stands behind a wide variety applications in automotive industry, civil engineering, packaging and transportation of fragile goods. The quasi-static mechanical properties of the foams, which belong to a large group of materials with cellular structure, were studied intensely over last fifty years. The results of these multiple studies were carefully analyzed by Gibson and Ashby [1], who suggested a series of useful phenomenological relations between the densities, moduli, Poisson's ratios, and collapse stresses of the foams and the properties of the bulk material the foam was made of. Similar relations for foams' moduli, yield or collapse stress, etc., were obtained as the result of the micromechanical study of the struts of the foam skeleton [2]. The dynamic response of the foams, essential for their applications, was not addressed in these studies. An important feature of the dynamic response of the polymeric foams is their strong strain rate sensitivity [3]. The influence of the strain rate on the mechanical response of foams was revealed in drop-weight [4–6] and impact sleds [7] experiments and was found to be crucial for their energy absorbing ability. Unfortunately the results of these experiments do not provide data for a constitutive description of the studied material. This problem was partly solved by use of the SHPB (Split Hopkinson Pressure Bar) [8–11] study of the dynamic response of the foams. This method allows obtaining the stress-strain relations of the foams at the relevant (10^2 s^{-1} - 10^3 s^{-1}) strain rates providing valuable information for the constitutive modeling of the foams and for energy absorption estimates.

Gas gun driven planar impact experiments are widely used for studying the dynamic response of metals, ceramics and polymers up to strain rates of about 10^6 s^{-1} and higher [12]. The adjustment technique used in such experiments allows one to create exact uniaxial strain boundary conditions in the impacted sample. As a result, the initial parameters of the shock-induced stress pulse traveling through the studied sample are precisely defined. The response of the impact-loaded sample being monitored by a Velocity Interferometer System for Any Reflector (VISAR) [13] provides accurate constitutive information about the studied sample. One motivation for the present work was to explore the possibility of using the VISAR-instrumented gun-driven planar impact experiment for obtaining such constitutive information about flexible polymeric foam. Another reason was dictated by the need to close the gap between the highest loading rates of SHPB technique, $\sim 10^3$ s^{-1}, and the lowest of the planar impact, $\sim 10^4$ s^{-1}. Addressing these two issues prompted us to perform a series of planar impact experiments with high density flexible polyurethane foam, accompanied by VISAR monitoring the velocity w of the free sample surface.

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2. Material and experimental

Planar impact experiments with the polyurethane foam were performed with 59-mm bore 4-m long gas gun of the Laboratory of Dynamic Behavior of Materials at Ben-Gurion University. The 8.9 ($\pm$0.1)-mm thick sheets of high density ($\rho_0 = 409 \pm 4$ kg/m^3, some 65–66% open porosity) flexible polyurethane foam were received from PLASAN Ltd., Sasa, Israel. The structure of the studied foam, the dense packing of interconnected hollow spheres of 100–150 - micron diameter, is shown in Fig. 1a. Prior the impact experiments, the foam was tested in quasi-static compression using a 5587 Instron testing machine equipped with the Instron 2501 150-mm compression platens and an Instron 2601 deflection sensor. The results of this test with a 55 mm thick (6 layers of 8.9-mm thick) foam sample are shown in Fig. 1b.

The presently studied material has a stress-strain diagram that is typical for foams [1], with an inflection point at approximately 0.13 MPa and collapse stress, determined as shown in the insert of Fig. 1b, equal to 0.07 MPa. The initial, straight, segment of the diagram has a slope of about 0.78 MPa which may be interpreted as the foam's Young's modulus.

For 8 of 10 planar impact tests (marked as PFA to PFH in Table 1) both the samples and the impactors were prepared from 60 × 60 mm^2 square pieces cut from the foam sheets. The projectiles equipped with the foam impactors were prepared according to the following procedure: the foam square was glued (two-component DEVCON 5 min epoxy) to the front part of 55-mm diameter, 11.8-mm thick plane-parallel polymethylmethacrylate (PMMA) disk, and the foam surplus over the 55-mm diameter was removed by turning. In order to provide shorting of the velocity and trigger electrical charged pins, the 14-μ thick aluminum foil ring was glued, using the same epoxy, to the front surface of the foam impactor. The back surface of the PMMA disk was glued with Loctite Super glue to the front edge of the hollow aluminum cylinder sabot. Finally the rear edge of the sabot was closed with a PMMA lid with an O-ring. In these eight tests and in the ninth test PFE1 where the sample was made of 5.5-mm (instead of 8.9-mm) foam layer, a similar sample assembly was used. The rear surface of the square foam sample was glued on a polyvinyl chloride (PVC) 100-mm diameter and 5-mm thick disc with a 45-mm diameter central hole. In order to provide reflection of VISAR beam, a piece of 14-μ aluminum foil was glued on the rear surface of the sample. The disk with the glued sample was fixed on the base ring of the double-tilt sample holder, whose parallel orientation to the front of the projectile had been preliminarily adjusted with an accuracy of 0.1 mrad. The schematics of these experiments are shown in Fig. 2a. In the tenth experiment, aimed at measuring the dynamic tensile (spall) strength of the foam, the impact was produced by a free-of-foam PMMA disk (primary impactor) on the 1-mm thick foam sheet (secondary impactor) separated from the sample by a spacer ring of 5-mm thickness. As result, the foam sample (Fig. 2b) was struck by a thin foam impactor.

The impact velocity, ranged from 43.5 to 605 m/s, was controlled by electrical charged pins. The uncertainty of the measurement of the impact velocity did not exceed 1% of the measured velocity value. The impactor-sample misalignment controlled by the trigger pins did not exceed 1 mrad in all experiments. Depending on the impact strength, the velocity of the rear sample surface was monitored by VISAR with delay lines providing velocity constants of 96.4, 224.0, and 407.2 m/s per fringe. The parameters of the ten planar impact experiments are listed in Table 1.

3. Experimental results

The VISAR-recorded velocity histories obtained after symmetric planar foam–foam impacts are shown in Fig. 3a–c.

Except for the waveform obtained after the weakest impact, the waveforms shown in Fig. 3 are characterized by a two-wave structure marked as P1 and P2 in Fig. 3a. The PFE1 test was performed in order to show that the presence of the P2 wave is caused by interaction of the unloading wave generated at the rear surface of the sample, with the reloading wave generated at the interface between the foam impactor and the PMMA backing. The stress σ - particle velocity u diagram and the time t - distance (Lagrangian) h diagram of Fig. 4 are to illustrate such interaction in the case of the PFE and PFE1 tests. Since both the samples and the impactors are made of the same foam, the particle velocity u_1 behind the shock fronts P1 propagating through both the sample and impactor with velocity U_S is equal to one half of the impact velocity. Accepting for both shocks the same impact velocity equal to $v_0 = 312$ m/s, yields for the particle velocity $u_1 = 156$ m/s. The amplitude of this impact-generated shock is σ_1 (Fig. 4a). At the arrival of the shock at the sample free surface it acquires velocity equal to 196 m/s. In the absence of the PMMA backing, the rear surface of the foam impactor should be decelerated from 312 m/s to 106 m/s. The presence of the PMMA backing results in the reloading of the impactor material from state with stress σ_1 to state with stress σ_2.

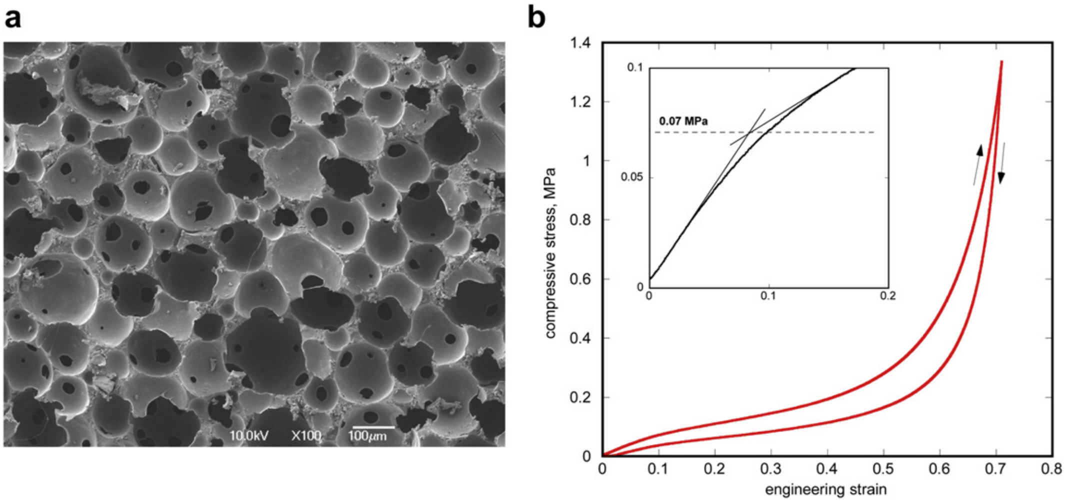

Fig. 1. SEM image of the cross-section of the studied polyurethane foam (a), and stress-strain diagram obtained after quasi-static compression tests performed with a 55-mm initial thickness foam sample. The strain rate in the test was $\dot{\varepsilon} = 1.5 \times 10^{-3}$ s^{-1}. The insert shows the determination of the collapse stress.