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Adiabatic shear failure of a syntactic polymeric foam

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Abstract

The recent tragedy of the Columbia shuttle has drawn much attention to the potential damage that may result from high velocity impact of foam on structural components. For obvious reasons, the emphasis was put on the structure rather than on the foam itself. We performed impact tests of polyurethane foam cylinders on various metallic plates, using small lightweight ($m \approx 1.4$ gr) cylinders launched at velocities in the range of 235–280 m/s. In addition to the resulting structural damage, we observed a peculiar and previously unreported failure mode for this kind of foam, which bears a high similarity to adiabatic shear failure. In this paper, we describe and discuss the essential results of the study with emphasis on the new failure mechanism for dynamically loaded polymeric foam.

Keywords: Adiabatic shear; Syntactic foam; Dynamic failure

1. Introduction

Common polymeric foams are seldom purposely exposed to dynamic loads, except for specific shock absorbing purposes, so that most of the studies to date concentrate on the dynamic mechanical characteristics of these materials (mostly stress–strain curves, see e.g. [1]). The dynamic failure mechanisms are seldom documented, with the exception of a recent paper by Song et al. [2], as opposed to quasi-static loading situations which have drawn much attention in the last decade, as can be found e.g. in Gibson and Ashby's monograph [3]. For this general class of cellular materials, several analytical and experimental works have shown the important role played by the localization of inelastic deformation in the form of narrow bands of buckled cells which are analogous the commonly observed shear-bands in metals (see e.g., [4,5]). A remarkable exception can be found in a recent study of a natural cellular material, balsa wood subjected to impact loading [6]. In this work, a systematic investigation of various grades (densities) of balsa shows a rich variety of failure mechanisms, all of which have in common the localization of inelastic deformation by cell buckling or kink banding. However, the final failure and fragmentation of this material were not addressed, due to the specific testing procedure based on a Kolsky bar where the specimen is sandwiched between two rigid metal bars and gets subsequently crushed. Impact behavior of foams is almost undocumented and would have probably remained so if the recent tragedy of the Columbia shuttle had not drawn attention to the structurally harmful effect that can result from the impact of relatively large chunks of foam on structural panels (NASA report, Internet [13]). In a series of experiments, foam cylinders have been shot using gas guns against various structural panels to identify the type of damage inflicted. However, no special attention was paid to the nature of the failure mechanisms of the foam projectile themselves. The goal of the present study was to investigate the high rate failure mechanisms of a commercial polymeric syntactic foam, when used as projectiles in high rate impact experiments.

2. Experimental

The investigated material is a commercial, most likely polyurethane, syntactic foam used for packaging applications. No information was available on the microstructure,

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Table 1
Experimental parameters

Experiment	Thickness [mm]	Impact velocity [m/s]	Resulting damage
Commercial Al	1.59	≈ 280	Marked bending
2014 Al alloy	1.51	≈ 235	Severe denting
Steel cookie lead	0.3	≈ 235	Severe denting

Note that the impact velocity is an upper bound as it does not take into account air resistance to the projectile's motion.

quasi-static mechanical properties and porosity of the investigated material. The measured density was found to be 200 kg/m^3. Lightweight (1.4 gr) projectiles, 12.7-mm diameter and 55 mm long, were machined from foam blocks. The projectiles were launched by means of a 12.7 mm bore diameter compressed air gun, and their velocity was assessed from the air pressure, gun barrel length and mass of the projectile using standard gas dynamics concepts [7]. The calculated projectile velocity is an upper bound as the air resistance to projectile propagation is not taken into account. The target consisted of metallic plates (1100 and 2014 Al., low carbon steel) that were positioned 15 cm away from the gun muzzle. The plates were backed by a very soft and compliant polymeric foam backing and were unsupported otherwise. Upon firing the gun, the fragments of the projectile were collected for examination and damage inflicted to the plates was assessed visually. Table 1 summarizes the experimental conditions and results.

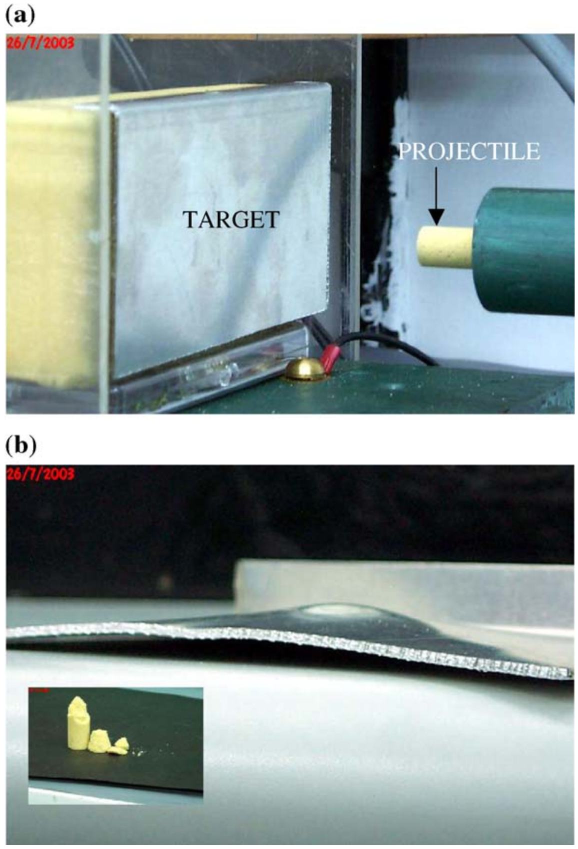

Fig. 1. Impact experiment. (a) Experimental setup, (b) damaged aluminum plate. Insert shows the fragmented projectile.

3. Results and discussion

A typical target, before and after impact, as well as the recovered projectiles are shown in Fig. 1. In all the cases, we noted severe structural damage consisting of severe denting and/or bending of the plates. Such damage is surprising given the light weight of the projectiles on the one hand, but can nevertheless be rationalized in terms of kinetic energy imparted to the projectiles. This damage will not be discussed further as this is not the main finding of this study. All the recovered projectiles showed surprisingly similar characteristics. First, it was noted that the projectiles failed in two distinct main pieces, rather than by a multiple fragmentation or disintegration process. The more striking observation is that the fracture surface consists of two matching and well-defined truncated cones. The length of a typical conical fragment is 13 mm for the upper diameter and 7 mm for the lower diameter. The characteristic semi-apex angle is 17° (Fig. 2). Scanning electron fractographs are shown in Fig. 3. The top and side fracture surfaces of the conical fragment confirm the fact that the material is a syntactic foam, as witnessed by the large number of cenosphere (microballoons) fragments. The side fracture surface comprises a much larger number of debris than the top normal surface. In addition, close examination of the side surface reveals characteristic plastic deformation marks in the polymeric matrix that were not discerned on the top surfaces. Similar features were reported by Gupta et al. [8] in a detailed study of syntactic (epoxy based) foam's static failure, and were unambiguously attributed to shear fracture. These authors also pointed out that the tendency to shear failure is more pronounced for specimens of a high aspect

Fig. 2. Broken polyurethane foam projectiles. Note the uniformity of the failure mode: in all the cases, a truncated conical plug is formed.

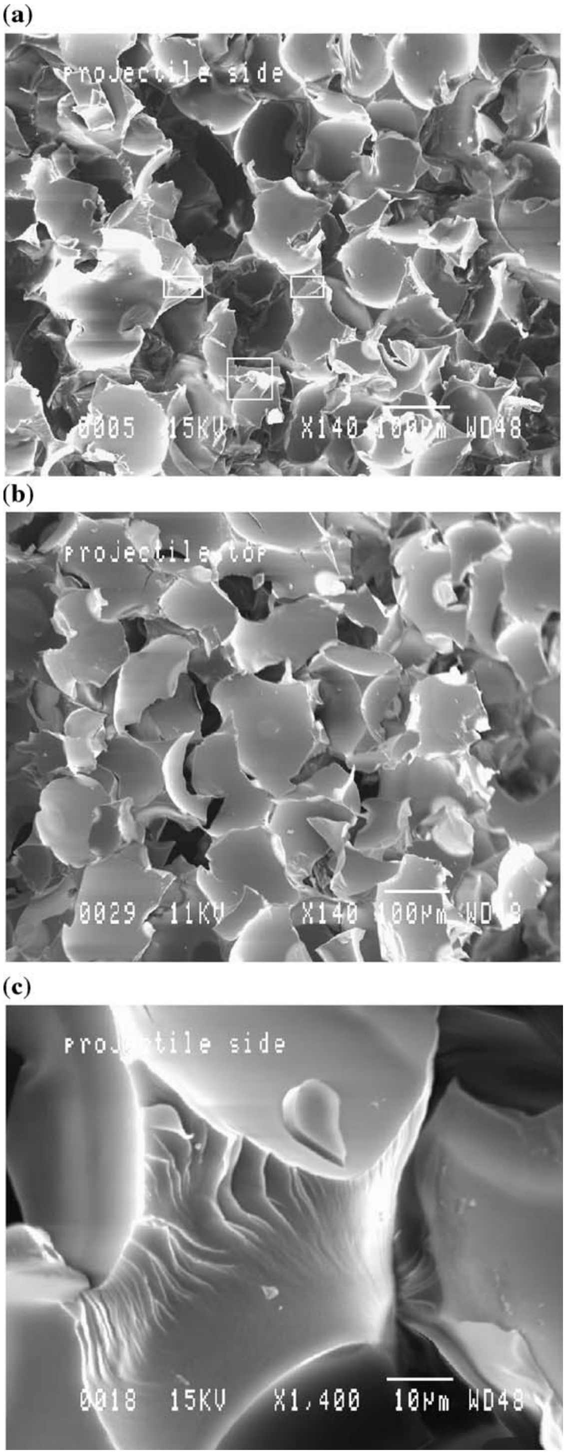

Fig. 3. Scanning electron fractographs. Panels (a) and (b) are taken from the side (shear) and top (tensile) surfaces of a conical fragment, respectively. The white rectangles on panel (a) outline typical plastic deformation features of the polymeric matrix. Such features are typical of shear failure, and are shown in panel (c).

ratio of 0.91. Song et al. [2] investigated lighter epoxy foam projectiles with an aspect ratio of 0.34. In the present case the aspect ratio of our projectiles is much larger and equals 4.33. However, despite the geometrical difference, these authors identified a tendency for strain rate softening at high strain rates, along with the formation of localized damage at 45° with respect to the compression axis. Thus, the present observations emphasize the shear nature of the failure mechanism(s), in accord with Gupta et al. [8] and Song et al. [2]. It should also be noted that many polymers exhibit a tendency to localized shear failure at high strain rates, accompanied by a noticeable temperature rise. (see, e.g. [9,10]). The observed temperature rise is coincident with marked strain softening of the material. The type of foam investigated in the present study has not been tested at high strain rates, including temperature measurements and subsequent fractographic characterization, to the best of our knowledge. Yet, due to the high strain rates involved in the present experiments, the deformation process may be viewed as adiabatic [9]. The combination of shear failure and rapid (hence adiabatic) deformation process lead to the conclusion that the failure mechanism can be further identified as *adiabatic shear failure*. While adiabatic shear failure is well documented for several metals and bulk polymeric materials, there is no previous report of the operation of this mechanism for polymeric foams. Adiabatic shear failure is promoted by shear localization, generally accompanied by a noticeable temperature rise as a result of the thermo-mechanical coupling by which the excess mechanical energy that is not stored into the microstructure is dissipated as heat. As an example, local shear strains of the order of 19, and local temperatures of several hundred degrees have been observed in steel (see e.g. [11,12]). At this stage, it appears that future research on this material should include temperature measurements close to the anticipated shear failure zone. Adiabatic shear is promoted by shear stresses, so that it is generally observed more frequently in dynamic torsion experiments than in dynamic compression. The present experiments bear a definite analogy with the so-called Taylor impact test which consists of having a cylindrical (metal) specimen impacting a rigid wall at high velocity to assess its mechanical properties [12].

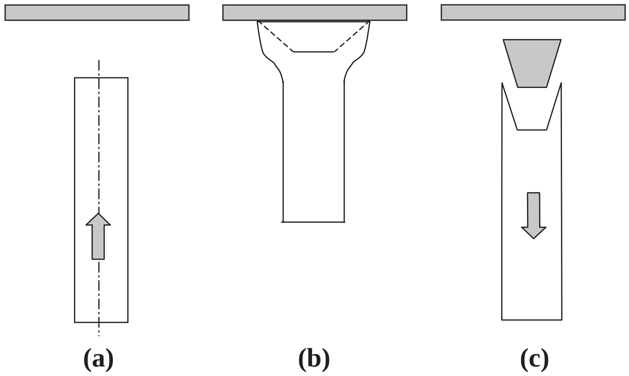

Fig. 4. Schematic description of adiabatic shear band formation during foam impact. (a) The impacting projectile; (b) mushrooming of the projectile impinging upon the target. The dashed lines illustrate the locus of maximal shear stresses where the adiabatic shear cone forms and fractures along these lines. The solid part of the cone indicates intact material. (c) Final tensile separation following bouncing back of the projectile.

The deformation of the projectile is not uniform and the impacting part tends to develop a (truncated) conical shape. In such an experiment, adiabatic shear bands are frequently observed for those materials that are prone to develop localization. In our experiments, the target is by no means rigid, but it can nevertheless be considered to be so at least during the initial phase of the impact. In Fig. 4 we have plotted a schematic description of the deformation and fracture sequence of the projectile, along with the (truncated) conical shear surface locus for this axially symmetric projectile. Following the initial shear cone formation and fracture along its envelope, final tensile separation of the two fragments occurs at a stage where the projectile experiences a tensile wave upon its bouncing back off the target. The fractographic observations support this scenario since more damage of the cenospheres is observed in the sheared side of the cone than in the top section, thus confirming a tensile failure mechanism for the latter. For the present uniaxial compression test, the maximum shear stresses will develop at an angle of 45° with respect to the cylinder's axis. Keeping in mind that this applies to the deformed configuration, this scheme illustrates the point that an initial semi-apex angle of 45° in the highly deformed configuration reaches the lower observed value of 17° once the foam has recovered from the impact. As a final remark, it should be pointed out that the present study applies to a commercial material whose microstructure and composition are not well defined. Despite this limitation, it is felt that the original observation of adiabatic shear failure may apply to a wide range of syntactic foams, for which additional research work is required.

4. Conclusion

This work has reported the operation of adiabatic shear failure for impacting commercial syntactic polyurethane foam projectiles. This mechanism was not reported previously, and it could only be observed as a result of the Taylor-like type of experiments carried out during which the foam impacts a target rather than being crushed as in conventional tests. Additional modeling and experimental work is needed to fully analyze this phenomenon and extend it to various well defined grades of foam.

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