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A NOTE ON THE DYNAMIC FAILURE OF PMMA

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Abstract. This paper reports our results on the investigation of dynamic failure of PMMA. Two stages have been previously identified. Kolsky (1949) applied very small strains and noted a hysteretic stress-strain behavior. Walley et al. (1989, 1994) and Rittel (2000) reported a large stress drop past a maximum and reached relatively large strains for this material. Final failure of the specimen corresponded to its shattering. In the present work we performed interrupted dynamic loading tests, so that a stage could be reached at which a well developed network of microcracks forms without further evolution to cause final failure. This intermediate stage, between lack of apparent damage and complete comminution is identified as the region of initial stress decrease, past a maximum value.

1. Introduction. Dynamic failure of polymethylmethacrylate (PMMA) is considered as the brittle failure of a viscoelastic material for which high strain rate causes a predominantly elastic response. In his classical paper, Kolsky (1949) described what is currently known as the Kolsky apparatus (Split Hopkinson pressure bar), as a means to investigate high strain rate behavior of various materials. Among these materials, the dynamic compressive mechanical response of PMMA ("Perspex") was investigated. In this paper, a marked hysteretic behavior was noticeable, as the overall strain range was limited to a few percent (about 0.02). The author did not mention specimen failure, as the maximum stress level reached remained relatively innocuous for this material. Detailed studies of the dynamic behavior of various polymers, including PMMA, can be found in the work of Walley et al. (1989, 1994). These authors investigated the dynamic mechanical response of the material and they also documented the failure process using high-speed photography. The reported strain range is higher than that investigated by Kolsky, reaching 0.2. The recording of the failure process reveals cracking and shattering of the various investigated polymers, as failure mechanisms. Emphasis was not put on the correlation between the evolution of the damage and that of the stress-strain curve. In a different context, Rittel (2000)

presented results on the compressive dynamic stress-strain behavior of commercial PMMA, using a Kolsky bar. Here too, large strains were reached as the specimen failed completely by shattering. In these experiments, only small fragments of the material could (sometimes) be recovered. The stress-strain curve comprised three phases: an initially rising part (up to $\varepsilon \approx 0.15$) which reaches a plateau, followed by a slower decrease (up to $\varepsilon \approx 0.4$). The slow decrease is characteristic of gradual damage evolution (as opposed to brutal). However, none of these works did specifically address the various stages of the dynamic damage (initiation and growth) in relation with the stress-strain characteristics.
This note reports our results on the evolution of the dynamic damage process with the loading, thus bringing additional and complementary information to that found in the above mentioned work.

2. Experimental procedure. A total of 21 disks, were machined through the thickness of a commercial 12.5 mm thick PMMA plate. The specimen thickness to diameter ratio was kept to 0.5 as recommended, in most experiments. However, to increase the strain rate, the specimen thickness had to be reduced to about 2 mm which violated this recommendation. The disks were subsequently tested in a standard 7075 Aluminum–12.5 mm diameter Kolsky bar (Kolsky, 1949). The specimen-bar interfaces were lubricated with petroleum jelly, as recommended in the literature (Walley et al., 1989). The stresses and strains were determined from the incident and transmitted gage signals, after their correction for geometrical dispersion (Lifshitz and Leber, 1994). The strain rate varied according to the disk thickness. A combination of strain rates and maximum strain achieved was explored by selecting the thickness of the disk and controlling the velocity of the striker. The typical strain rates ranged from $3000 s^{-1}$ to $15000 s^{-1}$.

3. Results. Impact experiments show that commercial PMMA is a brittle material, capable of sustaining a limited inelastic deformation at high strain rate prior to shattering.
Preliminary experiments showed two kinds of behavior: *either* the material sustained the impact without apparent damage, *or* it shattered into a multitude of small fragments. Representative stress-strain curves are shown for each case in Figure 1a (loading-unloading) and 1b (loading and shattering) respectively. The specimen corresponding to Figure 1a discloses a hysteretic behavior, but it must be emphasized that the specimen has not been stressed until fracture. Examination under the light microscope did not reveal any evidence of damage.
The specimen corresponding to Figure 1b behaved quite differently as it shattered, and a well defined peak stress can be observed prior to fracture. In Figure 1a, we have included Kolsky's data and in Figure 1b Walley et al. (1989) data. In both cases a good agreement with these authors is noticeable.

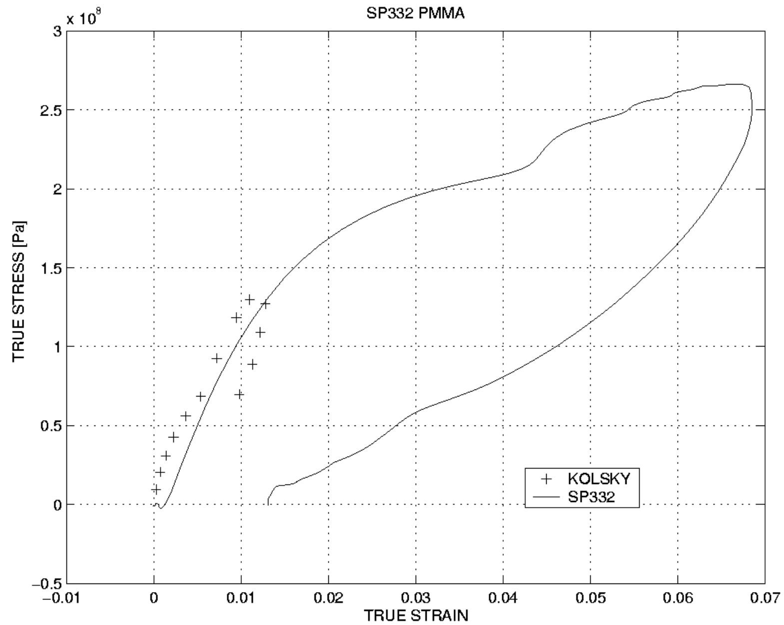

Figure 1a: Dynamic true stress-strain curve. Low overall strains: loading-unloading (nominal strain rate=$5000s^{-1}$). Hysteretic behavior, in accord with Kolsky's results (1949). The specimen did not fracture.

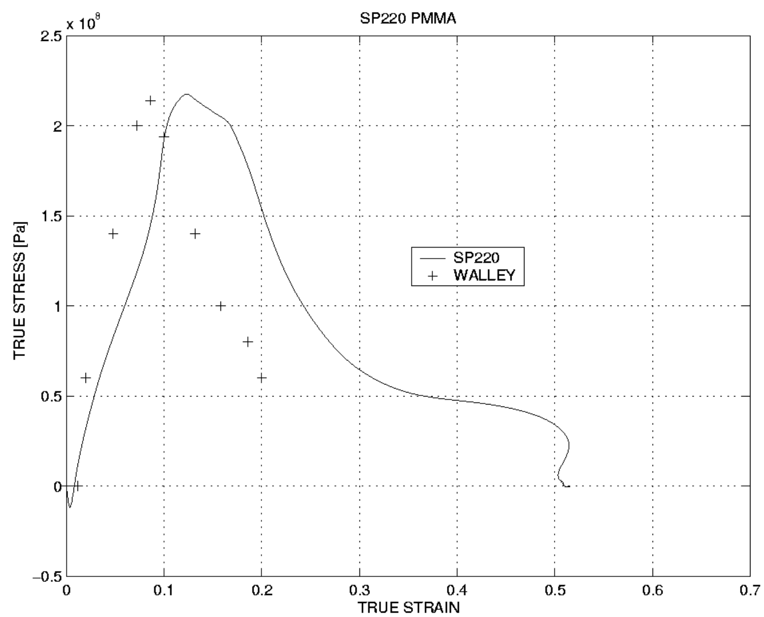

Figure 1b: Dynamic true stress-strain curve. Large overall strains: loading-fracture (nominal strain rate=$10000s^{-1}$). The specimen shattered. Walley et al (1989) results show a similar behavior.

A *subsequent* series of experiments was aimed at identifying a *threshold* at which damage would be identified (single or network of cracks) without total comminution of the specimen.
Here, the specimen thickness was reduced to 2mm and the gas pressure was varied systematically to identify the damage formation domain by varying the striker's velocity. When the pressure was not sufficient to cause overall specimen failure, a well developed network of cracks could be observed. Such a typical network of cracks is shown in Figure 2 along with the matching stress strain-curve in Figure 3.

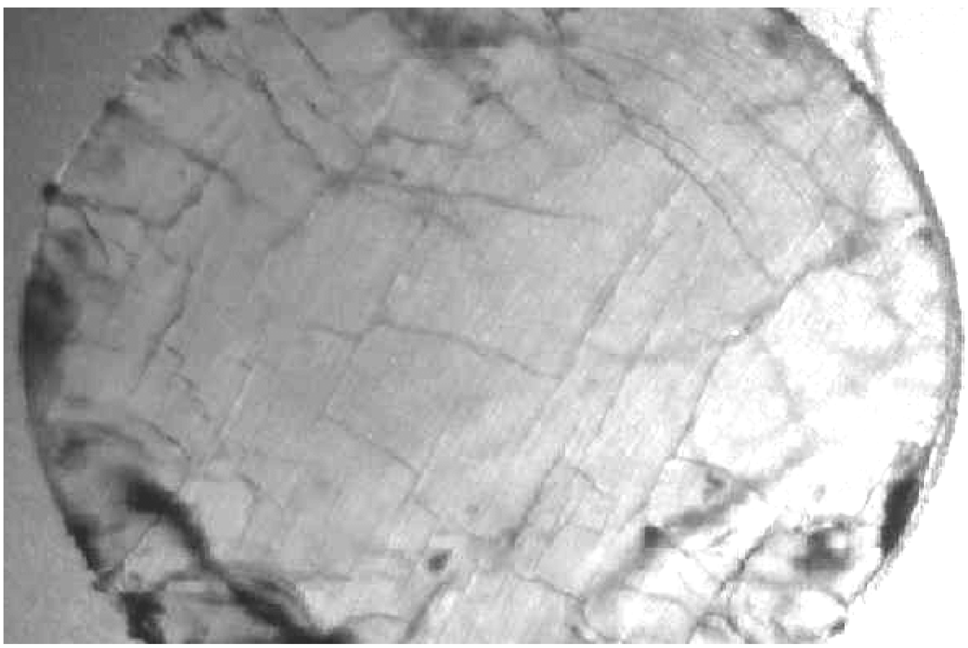

Figure 2: Typical network of cracks that developed prior to general failure of the specimen by comminution (specimen 410).

As a result of this series of experiments, one can now identify 3 distinct stages of the dynamic mechanical response and corresponding damage evolution of the PMMA disks, as follows:

- The first stage is characterized by a lack of apparent damage (such as microcracks) and it manifests itself by the hysteretic behavior in the stress-strain curve, as in Kolsky (1949). The material is loaded and unloaded by the stress pulse. This stage extends up to a stress of about 200MPa. For such behavior, exemplified by specimen 401 in Figure 3, the stress strain curve is continuously rising.

- The second stage, which develops at higher impact velocities, reveals the development of a network of microcracks which are apparently caused by radial stresses. Here too, the hysteretic behavior in the stress-strain curve is quite noticeable. For such behavior, exemplified by specimen 410 in Figure 3, the stress-strain curve reaches a maximum, followed by a short softening phase, which is terminated by the unloading. The stress pulse is of sufficient amplitude to initiate the damage (network of cracks). Yet its duration is too short to cause significant coalescence leading to final fracture. Stage 2 is thus the extension of stage 1.
- The last stage is that of microcrack coalescence. It manifests itself by the *decrease* in stress with increasing strain. By itself, stage 3 is the continuation of stages 1 and 2 as can be noted from the stress-strain behavior.This stage, wich involves most likely crack frictional effects, was identified by Rittel (2000) as responsible for the temperature rise measured in PMMA.

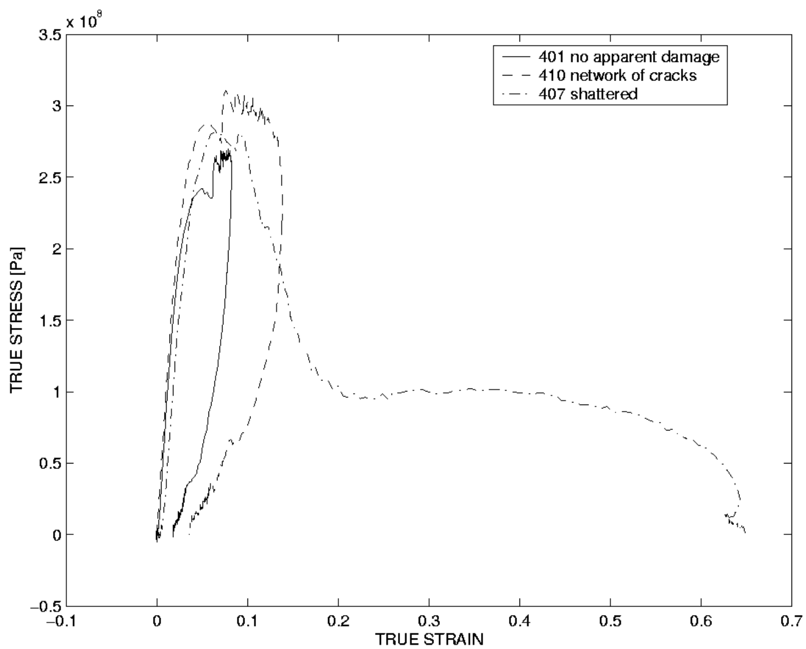

Figure 3: True stress-strain curves for 3 specimens with different levels of damage. .

4. Conclusion. Three distinct consecutive stages of the evolution of damage in dynamically loaded PMMA have been identified. For the first stage, characterized by a stress threshold, no visible damage is formed. The stress-strain curve increases continuously. During the second stage, characterized by initial strain softening past the maximal stress, a network of microcracks forms. In the last stage, characterized by a noticeable drop of the stress-strain curve, the microcracks coalesce to cause shattering of the specimen. This stage is exothermic.

These observations complement previous investigations of the dynamic failure of PMMA, in the more general context of the dynamic failure of brittle materials.

5. References.

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