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Studies of Film Effects on the Turbulent Mixing Zone Evolution in Shock Tube Experiments*

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1. The shock tube experiments [1]–[4] to study the turbulent mixing of two gases use a thin ($0.4-1\mu$m) polymeric film manufactured by the researchers. The experiments [1] used the film manufactured from vinyl chloride lacquer (L-type film); the experiments [2]–[4] (as reported by Dr. J.-F Haas) used the film manufactured from the commercially available compound MICRO-X (X-type film). The significant discrepancy between the experimental results [1]–[4] encouraged the search of the sources of this discrepancy, in particular to study the properties of thin films.

2. To study the film strength properties, a variant of method [5] was used to measure the sag value (S_f) of the diaphragm manufactured of the tested film fixed along the perimeter (2.5 cm in diameter) by one compressed air pressure. The pressure of the compressed air in the assembly increased with time so that the deformation of the film under test till the destruction had the rate $dS_f/dt \sim 0.5$ cm/s.

3. The properties of both film types were determined in a series of experiments (simultaneously in two assemblies).

Figure 1 presents the typical result for one of the experiments. The results of nine experiments for L type film indicate that the maximum (disrupture) value S_f ranges from 0.9 to 2.6 mm and from 4.4 to 8 mm for X-type film.

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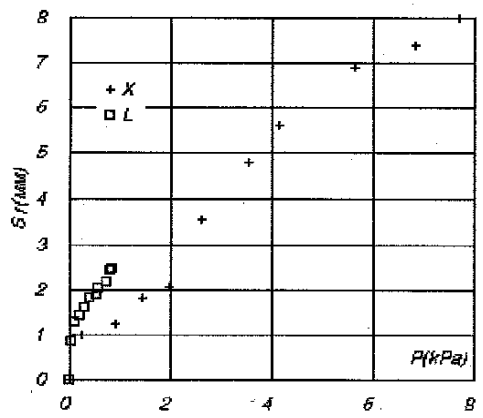

Figure 1: The sag value of X- and L-film diaphragm S_f as a function of the compressed gas pressure (experiment N18).

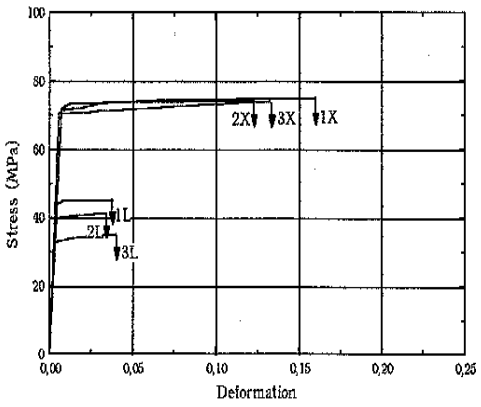

Figure 2: Deformation diagram for the L and X films obtained by processing as experimental data: 1 — experiment 13; 2 — experiment 15; 3 — experiment 16.

4. The experimental data processing yielded mechanical properties of the material as the dependence of the stress σ on the relative deformation ε at the polar point of the deformed film diaphragm ($\varepsilon = -0.5\ln(\delta/\delta_0)$) where δ, δ_0 are the current and initial film thicknesses.

The evaluation of mechanical film properties used the approximate numerical solution describing the deformation process of the thin round-shape membrane with a constant thickness and fixed contour affected by the uniform distributed pressure. It should be noted that the thin membrane approximation is quite correct for the thin films of interest. Our approach to the generation of the approximate analysis solution for the film sag is equivalent to the approximate calculations of the sag using one energy method [6]. The comparison of results obtained from the approximate solution and numerical deformation of the film demonstrated a good agreement.

Figure 2 presents the stress σ as a function of deformation ε for L and X film types obtained from the experiment processing. The arrows indicate the film disrupture.

The results presented show the distinct difference between the properties of different film types. The X films are more elastic and strong.

5. As will be shown below, the film destruction type under the shock acceleration greatly depends on the film thickness distribution over the surface area $\delta(x, y)$. In this view we made the thickness measurements of sub-micron range using the version of the method [7]. The method is to analyze the distribution of the reflection coefficient $n(x, y)$ over the surface of the film.

The measurements (using the Bruster angle evaluation) of the refraction index for

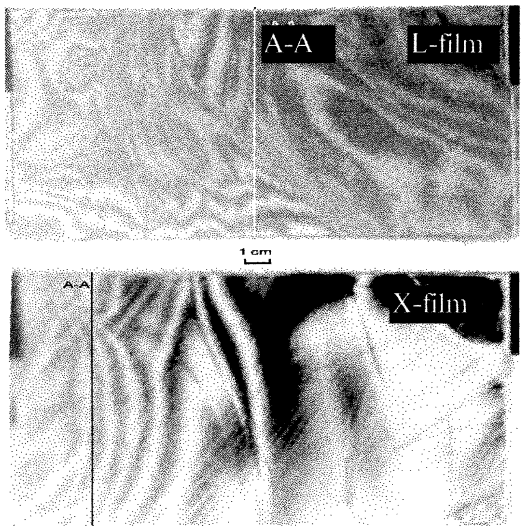

Figure 3: Interferograms for L and X films.

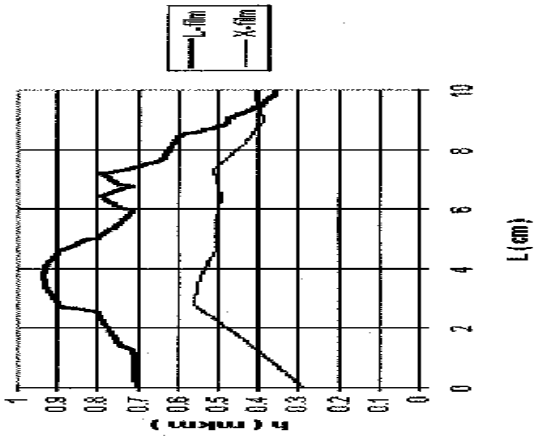

Figure 4: The film thickness measurements from A—A cross sections. (Figure 3).

the film material gave the following values: 1.54 ± 0.03 for X film and 1.58 ± 0.03 for L film on the visible light range.

The thickness $\delta(x, y)$ was measured for more than ten films of both types. Figure 3 show the characteristic thickness variations on the some cross-sections for L and X film types.

The method used allows to measure the film thickness in the range $0.12\,\mu$m–$1.7\,\mu$m with an accuracy not lower than 8 % for the resolution over x, y up to 4 mm.

The L films demonstrate often distinct fragments of millimeter range.

6. The numerical simulation of the variable-thickness strong film behavior in the experiments like [1] (when the shock wave accelerates the interface) used Lagrangian method.

We studied in details how the deformation levels are influenced by the geometrical film parameters (film thickness, thickness variation, perturbation wavelength) and the strength. In addition, we analyzed the process studied using the simplified analytical solution that gives a more profound understanding of the physical process and permits to verify qualitatively the numerical results obtained.

When the shock wave moves through the interface within a certain time interval ($\sim 10\,\mu$s), there exists the Rayleigh-Taylor instability condition: the light medium (a gas compressed by the shock wave reflected from the film) accelerates the heavy medium (film). After that the film deformation will continue by inertia and the film will resist

only due to the strength.

The film thickness variation (and hence the mass variation) will play the role of initial perturbation.

During numerical computations we considered the perturbation growth of the variable thickness film when the first shock wave moves through the gas interface for the typical experiment setup [1]–[4].

Figure 5 shows the maximum actual film deformation as a function of the perturbation wavelength and strength variations. The film thickness is $0.5\,\mu$m.

The experimental data for the evaluation of the geometrical film parameters indicate that relative thickness variation is about $0.1 - 0.3$ (for the average thickness $0.5\,\mu$m) with the characteristic perturbation wavelength $\lambda \sim$ 1–2 mm. The measurement of the film strength parameters showed that the threshold deformation of L type films is ~ 0.04 with the stresses about 35–45 MPa. For X type films this value as 0.12–0.16 with the stresses 70–75 Mpa (see figure 2). The numerical results show that when the first shock wave accelerates the L type film it can be destroyed to small pieces (curves 1,2). The fragmentation of the X film is unlikely (curve 3).

7. The experiments show that depending on initial conditions one can obtain the films (both L and X types) with different distribution patterns of thickness $\delta(x, y)$ — this can be very uniform or highly nonuniform and with small characteristic perturbation wavelength. Probably, for the homogeneous X film with relatively low level of initial perturbations of the shock front in the experiments [1]–[4], the film may break at the first shock wave as a single whole and then can be accelerated without fragmentation as an integral body.

We made the comparative experiments like [1] using the shock tube [1] but with the test section channel $80 \times 80\,\text{mm}^2$. The turbulent mixing zone width in both cases is comparable (Figure 6) and agrees with the results from [1] However the mixing zone pattern in both cases is very different: the L film breaks into small fragments with the size of a few millimeters or smaller; the X film destroys large fragments of several centimeters (Figure 7).

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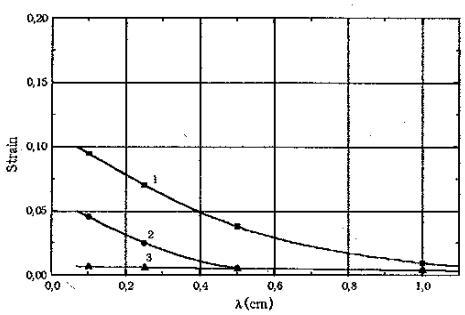

Figure 5: Maximum deformation of the film $0.5\,\mu$m thick ($\pm 0.1\,\mu$m) (because of the interface perturbation growth under shock acceleration) vs. perturbation wavelength λ. Curve 1 — the film with the ultimate tensile strength 1 — $\sigma = 32.5\,$MPa; 2 — $\sigma = 50\,$MPa; 3 — $\sigma = 72.5\,$MPa.

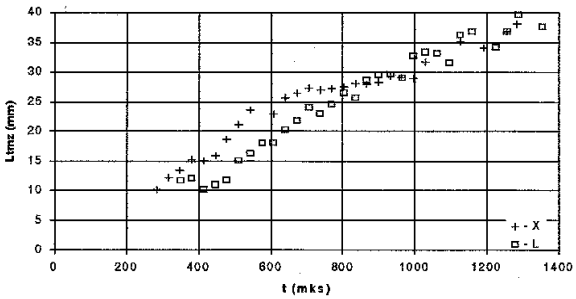

Figure 6: The turbulent mixing zone development.

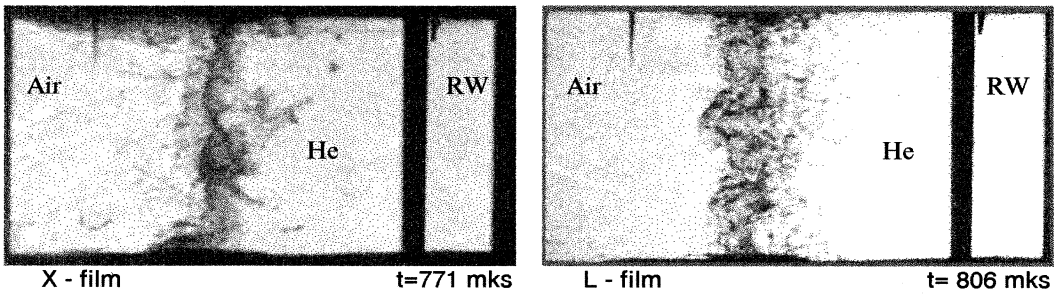

Figure 7: The experimental results for X film and L film. RW — rigid wall. Time t is counted of moment of shock wave to interface arrival.

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