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Effects of inside spallation of a coating on the debonding of its interface with a substrate subjected to a laser shock

M Boustie[1], **E Auroux**[1], **J P Romain**[1] **and M Jeandin**[2]

[1] Centre National de la Recherche Scientifique, Laboratoire de Combustion et de Détonique, ENSMA, BP 40109, 86961 Futuroscope-Chasseneuil Cedex, France
[2] Centre des Matériaux Pierre Marie Fourt, Ecole Nationale Supérieure des Mines de Paris, 91003 Evry Cedex, France

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Abstract

When applying a laser shock to a substrate with a coating in order to test the adhesion strength of the interface, traction can be generated not only at the interface, but also within the materials. The effects of a possible rupture of these materials prior to the debonding is analysed by shock wave propagation mechanisms and experimentally evidenced for plasma sprayed coatings of alumina on an aluminium substrate. An estimate of the bond strength and the spall strength of the coating is obtained by numerical simulation.

1. Introduction

The laser spallation process applied to the debonding of a coating on a substrate by applying the shock on the bare face of the substrate has been studied a great deal [1, 2]. In these studies, the interest is mainly focused on the generation of the traction at the interface. Actually, in most of the configurations, the interface is a weak point within the system, with usually a rupture strength much lower than that of the bulk components themselves. Therefore, the interface represents the most likely location to break when the system is under traction. However, it can happen under certain conditions that very high tractions are generated within the coating prior to occurring at the interface. A spall can then appear within the coating and the stress history of the interface will be subsequently modified. Such a phenomenon has been evidenced on a system built of an aluminium substrate with a 50 μm plasma sprayed coating of Al_2O_3. A simplified analytical study based on (space–time) and (pressure–particle velocity) diagrams evidences the chronology of the events throughout the various layers of the target. Thanks to this analysis, the implications of whether there is coating spalling or not on the stress history at the interface can be studied.

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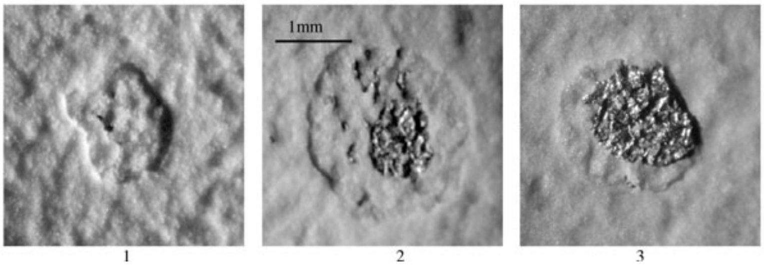


Figure 1. Observation of an Al_2O_3 coating damaged by increasing laser shock intensities with a pulse duration 3 ns, $\lambda = 1.064\ \mu m$ with a spot of 2 mm on the opposite face of the system.

Table 1. Observation of the coating of aluminium/Al_2O_3 targets irradiated with various laser intensities at 3 ns pulse duration. Numbers 1, 2 and 3 relate to references in figure 1.

Flux	Observed damage	
(GW cm^{-2})	At the interface	Within the coating
65	No damage	No damage
85	No damage (1)	Incipient spall
230	No damage	Spall completely ejected
247	Partial debonding (2)	Spall completely ejected
287	Full debonding (3)	Spall completely ejected

2. Experimental observation

The targets studied were constituted of an aluminium substrate (780 μm) coated with a plasma sprayed low porosity alumina layer (50 μm), rather brittle. Experiments have been carried out by direct irradiation of the bare face of aluminium by the high power laser facility of LULI (Laboratoire d'Utilisation des Lasers Intenses, Ecole Polytechnique, Palaiseau) with a 3 ns pulse duration. Various experiments carried out decreasing the incident intensity evidence different patterns for the spallation of the coating and the debonding. As evidenced in figure 1 and table 1, we observed two laser intensity thresholds corresponding each to a specific pattern of damage of the target. Above the first threshold ($I = 85$ GW cm^{-2}), we obtain a spall within the coating, located at 30 μm from the rear face, but no debonding at the interface. Increasing the intensity, we reach a second threshold ($I = 247$ GW cm^{-2}) for which the debonding is located at the interface beside the inner rupture of the coating. So, it seems that it is possible to get sufficient traction at the interface for reaching the debonding, even after a rupture occurs inside the coating, as long as the laser intensity applied to the substrate exceeds a threshold. The interpretation of this phenomenon can be found in the analysis of shock wave propagation in the structure.

3. Analytical study

In order to look for the origin of the tensile stress generated in various parts of the target, we perform an analysis of wave propagation on a space–time diagram (figure 2) according to the corresponding states located on the Hugoniot (pressure–particle velocity). Prior studies [3] evidenced that such an analysis could be reduced to the modelling of the propagation of the pressure profile arriving at the interface after propagation and attenuation while crossing the substrate. For the modelling, this profile is simplified by a shock followed by a two-step release, with amplitude and time characteristics matching those of the true profile. This true

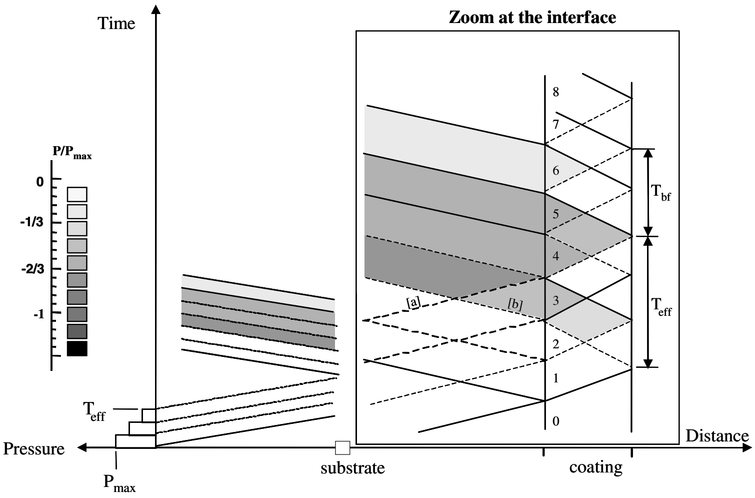


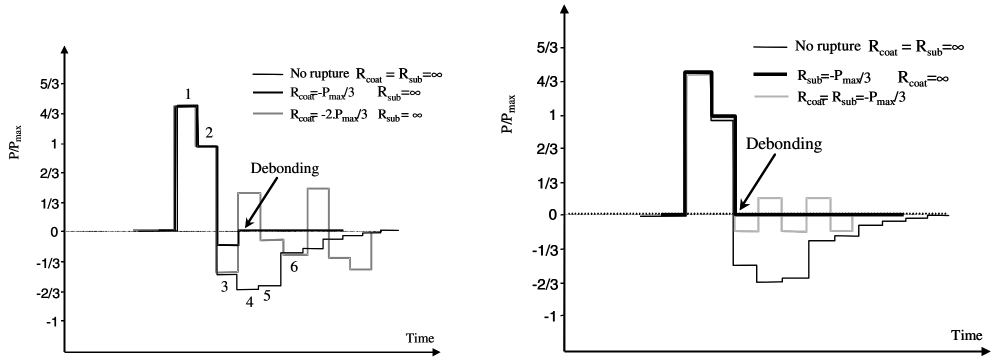
Figure 2. Space–time diagram corresponding to the case $T_{\mathrm{eff}}/T_{\mathrm{bf}} = 3/2$ with an impedance mismatch ratio between the coating and the substrate $Z_{\mathrm{coat}}/Z_{\mathrm{sub}}$ of 2 (shock waves (plain), release (dashed lines)) for a loading with an amplitude $P_{\max}$ and a duration T_{eff}. Only traction zones within the target are evidenced and the numbers refer to the pressure states of figure 3(a).

profile was previously calculated by a SHYLAC (Shock Hydrodynamic Lagrangian Code) numerical simulation of the propagation of the laser shock through the substrate. The profile's main characteristics are its amplitude $P_{\max}$ and its basis duration T_{eff}. Building the space–time diagram with the acoustic approximation (see figure 2), we determine the locations of compression or traction within the target. We observe successively traction zones with an increasing amplitude first within the coating, then at the interface and finally in the substrate. Hence, according to the respective values of the tensile strength of each zone, ruptures can be expected in every part of the target. The effect of these likely ruptures on the stress history of the interface is analysed, assuming a bond strength for the interface R_{int} equal to the highest considered value of the spall strength of the coating or of the substrate. Usually, the bond strength is lower.

Figure 3(a) shows the interface stress history in the case when a rupture occurs within the coating only for $R_{\mathrm{coat}} = -2P_{\max}/3$ and when the substrate does not break. The interface stress history is compared with the case when no rupture occurs. The coating's spallation results in a relaxation of the tensile stress at the interface. The debonding is not produced, assuming a bond strength $R_{\mathrm{int}} = -2P_{\max}/3$, but for lower bond strength it could be obtained. Assuming a value of $-P_{\max}/3$ for the coating and the bond strength, the spalling of the coating still allows the separation shown by the relaxation of interface stress to 0. When only the substrate spalls (figure 3(b)) for $-P_{\max}/3$, this same value is exceeded at the interface and the coating expelled. When both the coating and the substrate are spalled (figure 3(b)), the relaxation is stronger and tensions lower than $-P_{\max}/3$ are generated at the interface. So, in the case of a lower adhesion level, debonding is still possible. In both cases, even though a rupture occurs in the coating, it is still possible to apply traction at the interface.

4. Discussion

For the experiments performed with the system aluminium/alumina, numerical simulations show that the ratio $T_{\mathrm{eff}}/T_{\mathrm{bf}}$ is between 2.6 and 3.2. As for the ratio of shock impedance of the coating and the substrate, it is about 2. Hence, we are in a configuration close to that shown



-a- *-b-*

Figure 3. Interface stress history with a cohesive rupture within the coating in the case of an applied loading of amplitude $P_{\max}$ and a duration T_{eff} with $T_{\text{eff}}/T_{\text{bf}} > 1$ and $Z_{\text{coat}} > Z_{\text{sub}}$ ($Z_{c/s} = 2$). Comparison of the interface stress history without any rupture with: (a) the case of a rupture within the coating with two levels of coating spall strength R_{coat}, (b) the case of a rupture in the substrate and in both the substrate and the coating.

in figure 3. By increasing the laser intensity, we increase progressively the value of $P_{\max}$ and therefore the traction level amplitudes everywhere in the target.

For the intensity of 85 GW cm^{-2} (corresponding to a value of $P_{\max}$ of 2.3 GPa (accounting for the hydrodynamic decay), we observe a spall within the coating at 30 μm of the interface. The corresponding SHYLAC numerical simulation indicates a maximum induced traction at this location $R_{\text{coat}} = 1.85$ GPa $= 0.8\ P_{\max}$. For the higher intensity of 247 GW cm^{-2}, we observe a spall in the coating and the debonding at the interface. Performing a SHYLAC simulation of this experiment using the previous value for the spall strength of the coating, we can read a value of 1.15 GPa for the maximum tensile stress at the interface.

5. Conclusions

Hence, we have evidenced the effects of a cohesive rupture of the coating on the possibility of interface debonding by laser shock. The analytical study corroborated by experiments carried out on an aluminium/alumina system shows that for low intensities, a spalling within the coating yields too low a traction at the interface to achieve the debonding. By increasing the laser intensity, even with the occurrence of a spall in the coating, it is possible to find the debonding threshold at the interface. Using numerical simulation, it could be possible to determine the threshold traction conditions.

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