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SPALL PRESSURE IN COBALT ALUMINUM SYSTEMS

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INTRODUCTION

This is a review of experiments done to establish spall threshold for two Cobalt-Aluminum alloys: 69% Co and 31% Al, designated "hard phase" CoAl; and 93.1% Co and 6.4% Al, designated "soft phase" Co(Al). These experiments were completed under Michigan Technological University contract number 40717, Washington State University budget control number 2464-0090.

Samples and flyers used in these experiments were prepared by MTU. Samples were supplied as disks about 1/2 inch in diameter and approximately 3 mm thick. Flyers were also 1/2 inch disks and about 1μmm thick, except for two thicker flyers prepared by WSU from boule material supplied by MTU.

The soft phase Co(Al) targets supplied were: 2 @ polycrystalline practice samples designated P-1 and P-2; 6 @ single crystal samples, A through F; 4 @ target-flyer pairs, T-1 through T-4.

The hard phase CoAl samples supplied were: 2 @ practice bicrystals, PT-1 and PT-2; 6 @ single crystal targets, T-1 through T-6.

As received, the samples had an unacceptable edge rounding. This was eliminated by lapping after mounting in the guard ring. For this reason the target thicknesses reported in the shot data will be less than those shown in the data sheets from MTU.

MATERIAL PROPERTIES

In order to better characterize the state of stress in the sample, densities and sound speeds were measured for the several samples of the two alloys. From these data a linear Hugoniot relation was estimated, i.e., a relation between the final pressure and the particle velocity obtained in the shock process.

The Hugoniot will have the form

$$P = 10 \rho C U_p$$

where P is the final pressure in kbar;

ρ is the density in gr/cc;

C is the appropriate sound speed in mm/microsec;

U_p is the particle velocity in mm/microsec.

Density was measured by the displacement technique described in the Appendix. It has a probable error of 0.005 gr/cc. Ultrasonic sound speeds were measured by the pulse overlap method of Papadakis, [J. Appl. Phys., 35, 1474 (1964)]. Longitudinal sound speeds are probably good to plus or minus 0.01 mm/microsecond and shear waves speeds are good to plus or minus 0.05 mm/microsecond. The larger error in the shear speed is due to the difficulty of estimating coincidence of overlap because of a large dispersion in the alloy.

Data for the Hard Phase CoAl are:

$$\rho = 6.197 \text{ gr/cc}$$
$$C_L = 7.355 \text{ mm/}\mu\text{sec}$$
$$C_S = 4.689 \text{ mm/}\mu\text{sec}$$
$$C'_S = 3.671 \text{ mm/}\mu\text{sec}$$

The average of the density measurements given on the MTU data sheet sent August 17, 1982 is

$$\rho = 6.113 \text{ gr/cc}$$

Lemar (Lemar and Duvall, 1973) has reported a density for this alloy of 6.914 gr/cc. Assuming he was using the same material supplied for this work, his value is in error. Comparison with the above figures suggests the second and third digits were transposed. A corrected linear Hugoniot from his measured shock speed and the above density is

$$P = 395\ U_p$$

This relation will be used to estimate pressures in the reported hard phase CoAl experiments.

An interesting speculation about the dynamic yield can be made by combining the ultrasonic data for this alloy and the Hugoniot points measured by Lemar. In the elastic regime the material response can be characterized by a Hugoniot whose slope is the longitudinal sound speed C_L times the density and must, of course, pass through $P = 0$ at $U_p = 0$.

$$P = 455\ U_p$$

The slope of the plastic Hugoniot can be estimated for a short distance by the product of the bulk sound speed V_B * and the density. This line will pass through the measured Hugoniot points and its intersection with the elastic Hugoniot will be the Hugoniot elastic limit. An average of the data from Lemar's shots 79-021 and 79-022 give a Hugoniot elastic limit of 45 kbar.

Figure 1 is a graph showing plots of the elastic Hugoniot, Lemar's measured Hugoniot points, estimated plastic Hugoniot, and the corrected Hugoniot of Lemar.

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* The bulk sound speed was used to obtain this relations and is evaluated from $V_B^2 = C_2^2 - \frac{4}{3}V_S^2$ where V_S is taken as a simple average of the two shear speeds.

Data for the Soft phase Co(Al) are:

A linear Hugoniot from these data for the fully relaxed plastic state is

$$P = 376\ U_p$$

where P is the final pressure behind the shock front in kbar and U_p is the particle velocity in mm/microseconds. This is very close to the Hugoniot found by Lemar (Lemar and Duvall, 1973) viz $P = 380\ U_p$. Estimates of impact pressure reported in the various correspondences on this project were based on a copper Hugoniot; pressures stated in this report are based on the above data and will be somewhat higher.

Since the impacts were symmetric, that is, the flyer was of the same material as the sample, particle velocity is taken as half the impact velocity and impact pressure is estimated by the following relation

$$P = 188\ U_{pS}$$

where U_{pS} is the projectile velocity.

SPALL EXPERIMENTS

The basic geometry for all of the spall experiments was the same. The sample was mounted in a close fitting copper guard ring which was the same thickness as the sample. This copper ring also served as the sample mounting. It was attached with spots of glue to an adjustable target plate. This assembly was then adjusted until the impact surface was perpendicular to the axis of the launch tube. Alignment could be made to better than 0.5 milliradian.

The flyer was supported near is edge by an aluminum plate glued to a foam projectile. The flyer face was made perpendicular to the sides of the foam projectile by bending the aluminum plate. This could be done to an accuracy of about 2 milliradians. The configuration of the experiment just at impact is shown schematically in Fig. 2.

SOFT PHASE

Spall experiments on the soft phase Co(Al) are summarized in Table I. After recovery all samples, except sample A, were cut in the direction of the shock with a slow speed diamond saw. This surface was polished and etched with Nitol (Ethanol and 10% Nitric Acid). Microscopic examination of this surface was made for evidence of spall, usually at 30x and 100x. Experiments were done at pressures up to 44.8 kbar (sample A) using thick and thin flyers; in no case was spall detected. Pressure in the first group of experiments was 10.1 to 29.1 kbar. Since this produced no spall, an experiment was tried at 30.9 kbar using a thicker flyer. This also did not spall. An experiment at 44.8 kbar using the 4" gas gun, was not sectioned but ultrasonic testing showed no separation had occurred. The target arrangement is shown in Fig. 3, tilt in this experiment was not measured, but it is presumed to have been less than 0.5 milliradians on the basis of other measurements. This test had been intended to also produce data from a Hugoniot point using the VISAR*

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* VISAR = V elocity I interferometer S ystem for A ny R eflector. See Barker and Hollenbach. J. Appl. Phys. B. 43, 4669 (1972).

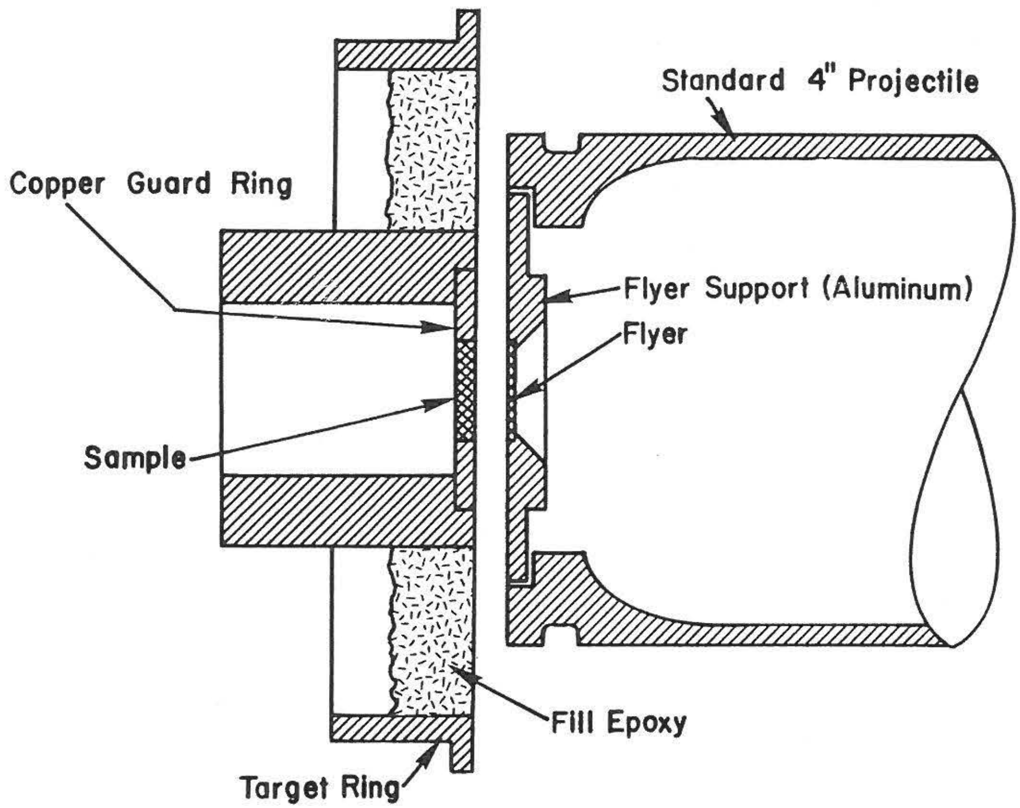

Figure 3. Experimental arrangement for spall experiment using 4" gas gun. Projectile shown just prior to impact.

Due to timing difficulties, this part of the experiment failed.

A series of experiments was undertaken to test the geometry of the experimental arrangement, substituting copper for the target and flyer with everything else the same. The results of this series are found in Table II. Spall in copper was found to occur between 21.1 and 24.8 kbar as expected (letter August 11, 1982).

WAVE PROFILES

Two experiments were done with soft phase Co(Al) to determine Hugoniot points. These were both symmetric impacts using the shorted quartz gauge (Jones and Halpin, Rev. Sci. Instr. 39, 258 (1968)) to measure shock pressure.

Pressure history at the rear surface of sample T-4, inferred from the current output of a quartz gauge affixed to the sample, is shown in Fig. 4a. Rise time was large, as shown, the maximum rate of rise being about 41.5 kb/microsecond. Peak pressure in the sample, inferred from the output of the quartz gauge was 9.2 kbar. Calculated impact pressure was 17 kbars. A sketch of the experiment in the x-t plane is shown in Fig. 4b. It was assumed in drawing this figure that the material work-hardens during compression to produce a compression fan, as shown. The rarefaction from the back of the flyer then overtakes the compression fan in the target, as shown, producing attenuation of the impact induced peak and limiting the maximum tensile stress induced in the specimen. Quantitative description of the stress fields produced in this material by impact would require an intensive study of wave profiles for different target and flyer thicknesses. This would be difficult to carry out without specimens of greater diameter than those available.

HARD PHASE

A summary of the impact experiments on the hard phase CoAl specimens is found in Table III. These shots were done with the same recovery technique used for the soft phase Co(Al) shown in Fig. 2.

These recovered samples were not sectioned since in all cases spall was obvious. The brittle nature of the alloy made a dramatic difference in the manifestation of spall over a narrow range of pressure.

The original estimate of spall stress was 20 to 24 kbar. This was very much above spall threshold and shots were done with successively lower impact pressures until no apparent separation occurred at 3.3 kbar. Two more shots were done at higher pressures to more closely bracket the spall threshold. The spall threshold is apparently between 3.3 and 4.3 kbar. It is probably not practical to further narrow those limits with material available and using this technique.

Table IV is the collected ultrasonic and density data on the hard phase CoAl.

DENSITY MEASUREMENTS BY DISPLACEMENT METHOD

Density measurement of solids is based on measurement of the sample weight and the weight of the amount of water displaced. The density is the former divided by the latter, times the relative density of water. Since the experiment is not usually conducted at the temperature where the density of water is unity, a correction must be made for this difference.

The sample whose density is to be determined should have a smooth and clean surface which must be wet easily by water. It should not have holes or an irregular surface which will trap air bubbles.

The water used for the displacement part of the procedure should be as pure as practical, at least distilled. Dissolved air is removed from the water by boiling vigorously in a narrow necked flask for several minutes. The water must then be allowed to come to the ambient temperature of the balance used for the measurement, usually left over night.

A small amount of household detergent added to the water does not materially change the density of the water but greatly increases its wetting ability, reducing the chance of trapped bubbles. The amount of liquid detergent on a clean glass rod after a smart shake is about right for 250 cc of water.

A hook is needed to suspend the sample in the water from the balance. The hook should be made of bare wire, copper "hook up" wire works well. Insulated wire, including varnish, does not wet well and leads to erratic results. The hook should be designed so as to support the sample with any broad, flat sides vertical, bubbles are not trapped under the sample. The things to avoid in making hooks are: any coils wound close together below the water level (these collect bubbles which are hard to detect or dislodge); wires twisted or close together through the surface (water will rise by capillary action between these wires leading to erratic results).

The sample, water, and balance, hooks, etc., should be allowed to come to ambient temperature before weighing begins. The weight of the sample should be determined to one tenth of a milligram, for very accurate results, a correction may have to be made for the bouyancy in air. Next, the sample is placed on the displacement hook and the water raised to submerge the sample; care in eliminating any bubbles on the sample or hook is important at this point. Weigh the sample and hook in the water. Without wetting any more of the hook or changing the water level, shake the sample off the hook into the vessel for the water. Determine the weight of the hook in the water at the same level as the original weighing.

The density is found by the following formula

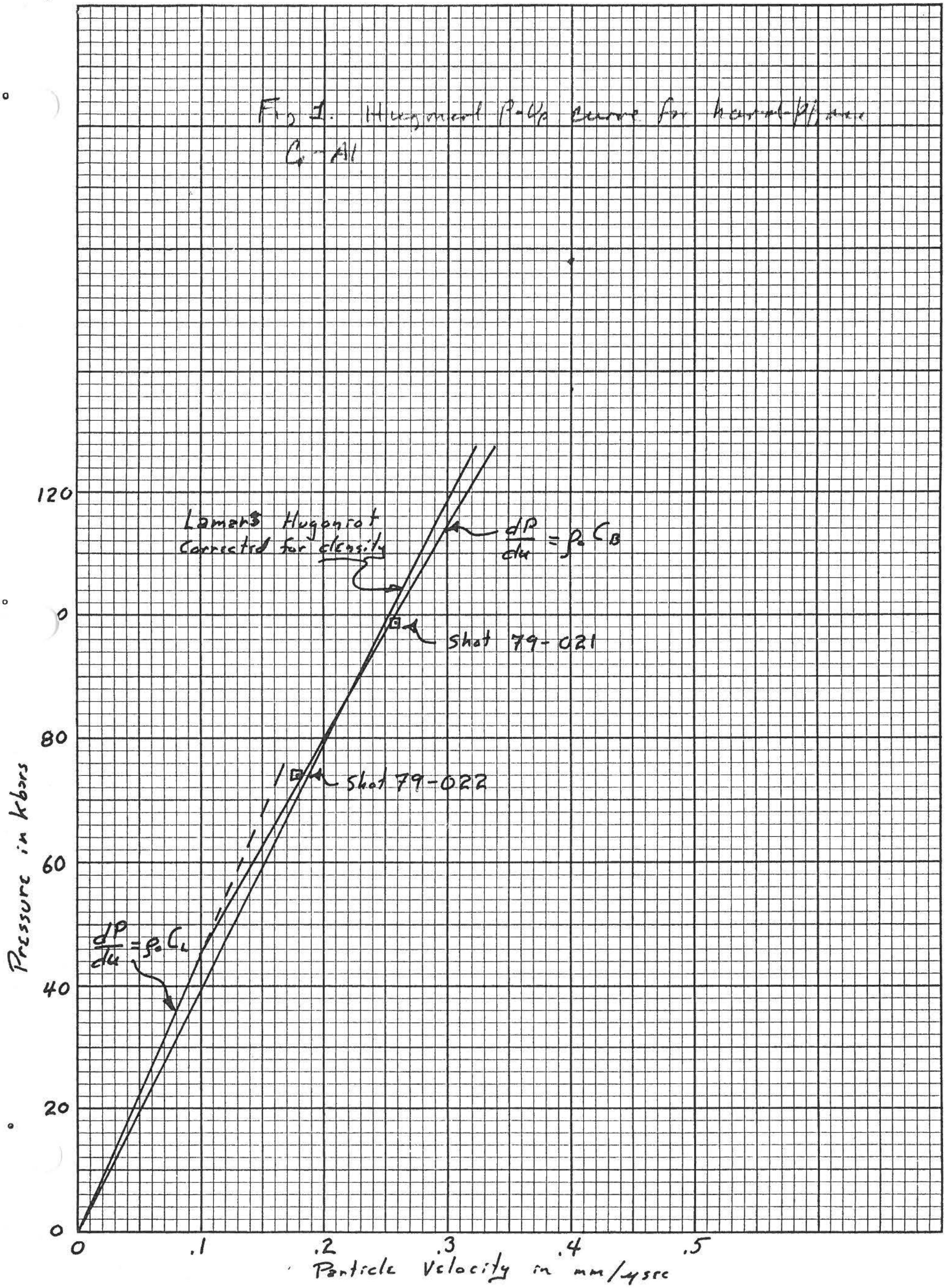

Fig 1. Hugoniot P-Up curve for [illegible] C-Al

INTERNAL REPORTS - 1983

1. S.C. Gupta, M.R. Williams, and Y.M. Gupta, "Shock Wave Response of Ytterbium Gauges up to 20 Kbars", Internal Report 83-01, August, 1983.

2. R. Collins, "Effect of Thermal Diffusion of Temperature for Thin Cells of Carbon Disulfide", Internal Report 83-02, September, 1983.