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SC-4747(RR)

THREE LOW-PRESSURE SPALL THRESHOLDS IN COPPER

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January 1963

ABSTRACT

Measured values of the three low-pressure spall thresholds in copper plate are presented. The two lower thresholds are original with this program. However, the incipient spall threshold or beginning of tensile damage corresponds rather closely in magnitude to the dynamic elastic yield strength of copper in compression. The complete spall threshold corresponds to the value determined by Rinehart¹ for copper.

Thresholds are presented in terms of pressure and pulse-width, and the effect of varying the pulsewidth with a given pressure is shown.

The experimental methods, including properties of the compressed-air gun, are discussed since they are applicable to most metals and many nonmetals.

* Now 7132

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Printed in USA. Price \$0.75. Available from the Office of
Technical Services, Department of Commerce,
Washington 25, D. C.

ACKNOWLEDGMENT

Many people gave aid and inspiration for this project. In particular, the author acknowledges the following:

C. D. Lundergan made the excellent experimental facility available and contributed helpful discussions.

R. E. Hollenbach and R. R. Williams prepared and aided in the firing of these shots.

Photomicrographs and other metallurgical work were done by D. R. Adolphson, R. D. Bland, and H. Romero.

Mutual discussions with L. M. Barker led to the tapered plug design and undoubtedly much of the other work.

An experiment by J. K. Landauer of the Lawrence Radiation Laboratory prompted these spall experiments, except the spall prevention test which was extended from an experiment by R. K. Warner, also of the Lawrence Radiation Laboratory.

The multiplane experiments very likely came from discussions of K. N. Kreyenhagen's work at Aerojet General.

TABLE OF CONTENTS

	<u>Page</u>
Introduction	7
Discussion	7
Experimental Methods	13
Conclusions	18
APPENDIX A -- METALLURGY	20
APPENDIX B -- SPALL PREVENTION	21
APPENDIX C -- MISCELLANEOUS FIGURES	23
LIST OF REFERENCES	27

LIST OF ILLUSTRATIONS

<u>Figure</u>		
1	Spall Thresholds	8
2	Spall vs Impulse for Given Pressure	9
3	Example of Wave Interactions With a Square Wave	11
4	Tapered Plug Spall Target	16
5	Residual Strength of Targets Using 1.5 μ s Square Pulses	17

LIST OF TABLES

<u>Table</u>		
I	Thresholds for a Pulsewidth of About 1 1/2 Microseconds	12
II	Spall Thickness	14
III	Spall vs Impulse	15

THREE LOW-PRESSURE SPALL THRESHOLDS IN COPPER^{*}

Introduction

When materials are compressed to pressures of tens of kilobars^{**} and then relieved to zero pressure, all within a few microseconds, spalling or scabbing often results. Spalling is the fracture of a material in tension caused by the interaction of two rarefaction waves.

Spalling can, of course, occur in varying degrees, thus leading to a total of four spall thresholds in copper, namely, the incipient, intermediate, complete, and ultimate spall thresholds (Figure 1). Moreover, these thresholds are somewhat dependent upon the type of copper used. Quantitative determination of the incipient and intermediate thresholds[†] is original with this program. However, the complete spall or detachment threshold as reported here is simply an edge-effect-free and, hence, lowered value of the threshold reported a decade ago by Rinehart.¹⁻³ The ultimate threshold, mentioned here for completeness, is well above the sixty kilobar upper limit of the present work, but has been observed by Dank, et al,⁴ McQueen and Marsh,⁵ and Glass.⁶

Spall studies provide: (1) realistic dynamic tensile strengths for design engineers, (2) a better understanding of solid state behavior, (3) data needed for many military applications, and (4) boundary conditions for equation of state programs in the negative pressure or tensile stress region.

Since 1912, when Bertram Hopkinson⁷ first explained spall, many experimenters^{1-6, 8} have conducted spall studies. However, almost without exception these experimenters used high explosives and ultrahigh pressures with their inherent control difficulties.

In December 1959, this spall program was initiated with a compressed-air gun to impact flat plates together. In this manner, spall thresholds in copper were determined using one-dimensional, plane, square waves, and known pulse widths. Thresholds are given in terms of impulse rather than pressure alone, and the need for this refinement is demonstrated. Figure 2 shows increasing spall damage with increasing initial pulse width for a given pressure.

The techniques discussed here are economical and give more precisely known input conditions than are possible with high explosives. Perhaps most important, the techniques have been shown to apply to aluminum, copper, steel, and various plastics. Spall thresholds, perhaps including the ultimate, for any ordinary material can be accurately determined by applying these techniques in conjunction with a high-velocity light-gas gun.

Discussion

Wave Shapes in Use

The tensile stress necessary to cause spall may be attained with two basically different wave shapes. Most observers use a pulse with a vertical shock front that is followed immediately by a sloping, exponential decay to zero pressure which continuously erodes the shock front. We might speak roughly of this as a "saw-tooth pulse." A pulse of this shape gives immediate tension when the vertical front reflects from a

^{*}This work was done under the auspices of the AEC.

^{**}One kilobar = 14,500 psi.

[†]The intermediate threshold was determined by Dr. Walter Herrmann of MIT and is based on his analysis of spall samples from this program. See Reference 20.

Incipient Spall
6 Kilobars, 115 ft/sec

Intermediate Spall
16 Kilobars, 250 ft/sec

Complete Spall
22 Kilobars, 410 ft/sec

Figure 1. Spall Thresholds
(1.5 μ s square pulse, Cu on Cu)

Figure 2. Spall vs Impulse for Given Pressure

free-surface back into the trailing pressure release region or rarefaction. Pulses of this shape may be produced either by detonating high explosives directly on the target surface¹⁻³ or by using high explosives to impact two plates at ultrahigh pressures where the initial square wave rapidly decays into a saw-tooth pulse.⁵

The second distinct wave, and the one used throughout this program, is the constant square wave. This wave has a vertical shock front followed by a constant pressure plateau and then, in this low pressure region, a near vertical rarefaction to zero pressure. The shock front reflects from a zero impedance boundary or free surface as a rarefaction to zero pressure. Then, when this rarefaction and the rarefaction which followed the original shock propagate together and interact, tension is created.

In these experiments, propagation distances are short enough and pressures are low enough so that the square wave is maintained until well after spall time. Certainly, the trailing rarefaction does not overtake and erode the shock front. See Figure 3 for an example of wave interactions with a square wave. For simplicity, the elastic precursor and the plastic shock wave are considered as one wave. The peak tension and the spall location are not affected by this simplification. However, if calculations of duration of tension were being attempted, the elastic precursor would have to be considered.

Once tension is produced in a material, by any method, spall in varying degrees occurs, depending⁴ only on peak tension, duration of tension, and material properties. The inability to determine the duration of tension forces the use of the initial pulse width. Now let us discuss each of the three spall thresholds observed in this work. And for the sake of including all possible thresholds, we will also consider the ultimate threshold observed by others.

Nature of the Various Thresholds

According to the widely accepted Griffith theory^{9, 10} of fracture, brittle solids always contain microcracks. Applied stress concentrates at some of these microcracks, and, if the stress is of sufficient magnitude, causes them to grow into larger voids.

The incipient spall threshold is defined as the minimum pressure for a given pulse width which creates any visible spall fractures or voids. Obviously, whether a fracture is visible or not depends on how it is observed. In practice, these incipient spall fractures are found by polishing and cathodically etching (see Appendix A) the sample after a test. Then, any power of lens in the metallograph from 60X on up is sufficient to resolve grain boundaries and incipient spall fractures. Using a higher power lens than 60X does not detect more voids, but simply enhances those found at the lower power. For example, a standard magnification of 100X was used for the photomicrographs shown here, but no more incipient spalls were observed than in earlier observations at 60X. In summary, the incipient spall threshold is the lowest pressure for a particular pulsewidth at which spall fractures on the order of a grain diameter occur.

The intermediate threshold is the pressure for a given pulse width for which the residual strength of the material takes on a constant value. This constant value of residual strength is maintained until the material has been subjected to the pressure necessary for complete spallation.

The intermediate threshold is clearly a later stage of damage than the incipient spall threshold. However, for the intermediate threshold, a greater density of microcracks start growing than at the lower-stress incipient spall threshold. This greater density decreases the distance a crack must travel to unite with another crack. In addition, microcracks get a much greater acceleration from the higher stress at the intermediate threshold.¹¹⁻¹³ Crack tip velocities may range from 40 to 90 percent of dilatational velocity.¹⁴⁻¹⁵

The third and last threshold determined in the present work is the complete spall threshold. This threshold is simply the pressure with a given pulse width for which detachment or complete separation of the spall piece occurs. Also, it is simply a later stage of damage than either of the first two thresholds. That is, more initial spall cracks are created and more crack propagation occurs. And, the small amount of material which is not severed by crack propagation may be sheared by momentum differences in the material. Rinehart¹⁻³ found this threshold for copper to be slightly over 28 kilobars with an unspecified pulse width and unrelieved edge effects.

Figure 3. Example of Wave Interactions With a Square Wave

These three thresholds are definitely rate or time dependent. Halving pulsewidths from 1-1/2 to 3/4 microseconds increased the incipient and complete thresholds by 3 or 4 kilobars. The intermediate threshold as yet has only been measured for the 1-1/2 microsecond pulse width. But even so, it seems clear that when one speaks of "yield pressure," a pulse width should be specified. See Table I, parts 1 and 2. Initial spall fractures occur in 10^{-8} or 10^{-9} seconds according to various theoreticians. But then the amount of damage occurring depends on how long the cracks are allowed to grow while this pressure is maintained.

TABLE I - PART 1
THRESHOLDS FOR A PULSEWIDTH OF ABOUT 1 1/2 MICROSECONDS

Test No.	Projectile Plate Velocity (ft/sec)	Approximate Material Pressure (Kb.)	EFFECT				Projectile Plate Thickness (in.)	Target Thickness (in.)
			None	Incipient Spall	Intermediate Spall	Complete Spall		
1	113	6.1					0.120	0.238
Incipient								
2	125	6.8					0.122	0.251
3	133	7.2					0.115	0.253
4	154	8.4					0.124	0.250
5	169	9.2					0.124	0.194
6	171	9.3					0.117	0.244
7	175	9.5					0.123	0.194
8	185	10.0					0.125	0.225
9	249	13.5					0.118	0.226
Intermediate								
10	294	16.0					0.119	0.241
11	326	17.7					0.115	0.235
12	401	21.8					0.114	0.236
Complete								
13	420	22.8					0.138	0.256
14	462	25.1					0.116	0.236
15	463	25.1					0.120	0.239
16	477	25.9					0.119	0.232
17	493	26.7					0.122	0.256
18	513	27.8					0.121	0.243
19	580	31.5					0.132	0.238
20	584	31.7					0.121	0.230
21	674	36.6					0.119	0.231
22	676	36.7					0.121	0.239
23	728	39.5					0.120	0.231
24	799	43.3					0.122	0.237
25	832	45.1					0.117	0.240
26	924	50.1					0.118	0.238

TABLE I - PART 2

THRESHOLDS FOR A PULSEWIDTH OF ABOUT 3/4 MICROSECOND

Test No.	Projectile Plate Velocity (ft/sec)	Approximate Material Pressure (kb.)	EFFECT			Projectile Plate Thickness (in.)	Target Thickness (in.)
			None	Incipient through Intermediate Spall	Complete Spall		
1	125	6.8				0.059	0.251
2	154	8.4				0.062	0.250
3	169	9.2				0.061	0.194
				Incipient			
4	175	9.5				0.060	0.194
5	178	9.7				0.065	0.239
6	185	10.0				0.061	0.225
7	268	14.5				0.062	0.239
8	462	25.1				0.069	0.224
9	484	26.3				0.067	0.216
					Complete		
10	502	27.2				0.061	0.217
11	539	29.2				0.062	0.239
12	592	32.1				0.063	0.238
13	693	37.6				0.061	0.234
14	726	39.4				0.067	0.240

High above these thresholds that are strongly dependent upon crack propagation is a pressure and pulsewidth sufficient to cause initial spall fractures which detach the spall piece before any appreciable crack propagation can occur. In 1959, Dank, et al.,⁴ deduced by extrapolation that this ultimate spall threshold would be at about 160 kilobars. McQueen and Marsh⁵ at Los Alamos and Glass⁶ at the Ballistics Research Laboratory have measured this ultimate spall threshold in copper single crystals.

Experimental Methods

Air Gun and Instrumentation

A compressed-air gun with a 13-foot long barrel and a 4-inch bore is used to accelerate the projectile plates to as much as 1100 feet/second. Each projectile plate is glued around its periphery to a three-pound hollow-nosed foam-plastic cylinder which holds the plate normal to the axis of the gun barrel. Two "O" rings on the plastic cylinder prevent the accelerating air from degrading the vacuum between the projectile and target plates.

The gun barrel and the vacuum cavity behind the projectile plate are evacuated to an initial vacuum of 10 microns. Subsequent compression from the projectile closing on the target is mitigated by an expansion reservoir around the muzzle of the barrel.

A simultaneity of impact averages 1/4 microsecond per inch across the target. This deviation from normal impact is believed to have a negligible effect on spall results.

Projectile velocity and simultaneity are measured on each shot by a minimum-error, six-pin array of charged pins derived by Duff.¹⁶ The pin closures are recorded with an oscilloscope and camera. Reference 17 gives the lengthy mathematics needed to reduce the pin data. However, a much simpler and more accurate way to measure projectile velocity, tilt, and tilt orientation is described in Reference 18.

Targets and Projectile Plates

Projectile plates are 3.8-inch diameter flat plates of the thickness desired, with a 50-microinch rms surface finish, and flat to within 0.0005 inch. In examining the effect of varied pulsewidths at precisely the same initial pressure, it is necessary to use "multiplane" projectile plates.

The multiplane plates are essentially just seven flat regions of different thicknesses which impact a quarter-inch thick flat target plate. Because of the small differences in thicknesses (see Tables II and III and Figure 2), the scaling proposed by Trulio¹⁹ is not deemed necessary.

All targets are 6.5-inch diameter, 1/4-inch thick flat plates with 50-microinch rms surface finishes. Flatness and parallelism are specified to 0.0005 inch. The large target diameters are needed for mounting on the gun and for holding measuring pins. The usable target diameter for spall observations is slightly over three inches. The usable diameter of the target equals the projectile plate diameter less the region influenced by edge effects which is roughly twice the target thickness.

Targets for accurately determining the complete spall threshold present a special problem. Simple flat plates do not allow the spalled region to detach without a lot of shearing long after spall time. Hence, targets were tried with a circular groove cut to the intended spall plane from the free surface side. This delineated the spalled piece and reduced edge shearing, but around the periphery of the spalled piece, near the groove, spalling was prevented. As evidence, the spalled piece was curved by the retardation at its edges. This, as we learned later, erroneously raised the complete spall threshold by two or three kilobars.

TABLE II
SPALL THICKNESS

Test No.	Projectile Plate Velocity (ft/sec)	Approximate Material Pressure (Kb.)	Target Thickness (in.)	Projectile Plate Thickness (in.)	Mean Spall Thickness	Projectile Plate Thickness* Mean Spall Thickness
1	420	22.8	0.256	0.138	0.130	1.06
2	477	25.9	0.232	0.119	0.119	1.00
3-1	488	26.5	0.250	0.051	0.047	1.09
3-2	488	26.5	0.250	0.063	0.058	1.09
3-3	488	26.5	0.250	0.075	0.069	1.09
3-4	488	26.5	0.250	0.088	0.085	1.04
3-5	488	26.5	0.250	0.100	0.097	1.03
3-6	488	26.5	0.250	0.112	0.107	1.05
3-7	488	26.5	0.250	0.125	0.122	1.02
4	493	26.7	0.256	0.122	0.121	1.01
5	~ 500	27.1	0.248	0.120	0.120	1.00
6	513	27.8	0.243	0.121	0.121	1.00
7	580	31.5	0.238	0.132	0.133	0.99
8	594	32.2	0.257	0.128	0.126	1.02
9	674	36.6	0.231	0.119	0.122	0.98
10	693	37.6	0.234	0.061	0.058	1.05
11	~ 700	38.0	0.247	0.120	0.119	1.01
12	728	39.5	0.231	0.120	0.119	1.01
13	832	45.1	0.240	0.117	0.117	1.00
*Projectile thickness = 1/2 initial pulse thickness						

TABLE III
SPALL VS IMPULSE

Test No.	Projectile Plate Velocity (ft/sec)	Target Thickness (in.)	Projectile Plate Thickness (in.)	EFFECT			Approximate Material Pressure (Kb.)	Approximate Pulse Width (μ s)
				None	Incipient through Intermediate Spall	Complete Spall		
1-1	488	0.253	0.125				26.5	1.50
1-2	488	0.253	0.112				26.5	1.35
1-3	488	0.253	0.100				26.5	1.20
1-4	488	0.253	0.088				26.5	1.05
1-5	488	0.253	0.075				26.5	0.90
1-6	488	0.253	0.063				26.5	0.75
1-7	488	0.253	0.051				26.5	0.60
2-1	185	0.225	0.125				10.0	1.50
2-2	185	0.225	0.111				10.0	1.35
2-3	185	0.225	0.100				10.0	1.20
2-4	185	0.225	0.088				10.0	1.05
2-5	185	0.225	0.076				10.0	0.90
2-6	185	0.225	0.061				10.0	0.75
2-7	185	0.225	0.050				10.0	0.60
3-1	175	0.194	0.123				9.5	1.50
3-2	175	0.194	0.111				9.5	1.35
3-3	175	0.194	0.099				9.5	1.20
3-4	175	0.194	0.087				9.5	1.05
3-5	175	0.194	0.073				9.5	0.90
3-6	175	0.194	0.060				9.5	0.75
3-7	175	0.194	0.049				9.5	0.60
4-1	169	0.194	0.124				9.2	1.50
4-2	169	0.194	0.111				9.2	1.35
4-3	169	0.194	0.099				9.2	1.20
4-4	169	0.194	0.088				9.2	1.05
4-5	169	0.194	0.074				9.2	0.90
4-6	169	0.194	0.061				9.2	0.75
4-7	169	0.194	0.049				9.2	0.60
5-1	154	0.250	0.124				8.4	1.50
5-2	154	0.250	0.111				8.4	1.35
5-3	154	0.250	0.098				8.4	1.20
5-4	154	0.250	0.088				8.4	1.05
5-5	154	0.250	0.072				8.4	0.90
5-6	154	0.250	0.062				8.4	0.75
5-7	154	0.250	0.049				8.4	0.60
6-1	125	0.251	0.122				6.8	1.50
6-2	125	0.251	0.108				6.8	1.35
6-3	125	0.251	0.097				6.8	1.20
6-4	125	0.251	0.084				6.8	1.05
6-5	125	0.251	0.071				6.8	0.90
6-6	125	0.251	0.059				6.8	0.75
6-7	125	0.251	0.047				6.8	0.60

To eliminate this edge effect, a special tapered plug design was evolved. The center region of a flat plate is cut out on an angle of about 8 degrees with the normal such that the smaller diameter is on the impact side of the target. The outer portion or retaining ring is usable. But, because of machining losses, the inner plug is discarded. Then a new tapered plug is machined which fits precisely into the center of the retaining ring. The finished product appears to be a one-piece target. See Figure 4 for details.

NOTE:
Diameter of impact surface
of tapered plug $\cong$ 2.9 inches

Figure 4. Tapered Plug Spall Target

The complete spall thresholds in Table I, parts 1 and 2, are based on tapered-plug shots with negligible edge effects. The spalled piece of each tapered plug is extremely flat and is spalled over its entire surface.

Actual Determination of Thresholds

To determine the incipient spall threshold, cross sections are cut of samples fired at various low pressures with a particular pulsewidth. These cross sections are then etched cathodically as discussed in Appendix A. Then the central, edge-effect-free, region of each sample is scanned with the metallograph at 60X until spall fractures are detected. For certainty they are also scanned at 300X.

The incipient spall threshold, of course, is bracketed by the undamaged sample tested at highest pressure and the sample with spall damage tested at the lowest pressure. Incipient spall thresholds for four different pressure and various pulsewidths may be seen in Figure 2. Clearly, the incipient spall threshold is somewhat arbitrary and dependent upon the etching and optical techniques chosen.

The intermediate spall threshold was determined as follows: The author sent spall samples fired at various intermediate pressures to Dr. Herrmann at MIT. Previously, each of these samples had been cross-sectioned and etched chemically (see Appendix A). Regretfully, not enough samples were sent to determine the intermediate threshold for the 3/4 microsecond pulsewidth. The intermediate threshold with a 1-1/2 microsecond pulsewidth is shown in Table I, part 1.

Dr. Herrmann cut tension specimens, including the spall plane, from each sample. These specimens were then pulled apart in a tension testing machine. In this way, he measured the residual strength across the spall plane. Figure 5 gives part of his results.

(1) The 24 kb data were obtained with a grooved target.
Edge effects prevented complete separation at 22 kb.

Figure 5. Residual Strength of Targets Using $1.5 \mu\text{s}$ Square Pulses *

Essentially, Figure 5 shows that samples tested below six kilobars with the pulsewidths used here have virgin-material strength. Samples tested above six kilobars lose residual strength quite rapidly as pressures approach fourteen kilobars. In fact, most cracks occur between 10 and 12 kilobars initial pressure. Surprisingly, samples tested between sixteen and twenty-two kilobars have a constant residual strength. Of course, samples tested above the complete spall or detachment threshold have zero residual strength. In Reference 20, Dr. Herrmann discusses the rate dependence of the spall process and explains his results. This threshold is not intended to be as sharply defined as the other two. The complete spall threshold is bracketed by the detached or completely spalled sample fired at lowest pressure and the intact sample fired at highest pressure. Certainly the intact sample has severe internal damage. Complete spall thresholds for two different pulsewidths are given in Table I.

* This graph by Dr. Walter Herrmann of MIT.

Pressure and Pulswidth Estimation

The tensile stress or negative pressure reached in each test can only be estimated at this time. For simplicity, each negative stress is assumed to be equal to the positive stress generated at the impact interface. The positive pressures are calculated with the Hugoniot conservation of momentum equation. And, fortunately, the impact velocities in the data tables have been accurately measured. Therefore, in years to come, when the negative equation of state of copper is known, the pressure data can be improved. Experimental and theoretical methods of deducing negative equations-of-state for metals are being developed in a Sandia-MIT joint effort.*

In the momentum conservation equation, $P = \rho U_s U_p$, the density, ρ , is accurately known to be 8.86 grams/cm³ for this copper. The particle or material velocity, U_p , is known on each test to within 3 percent. As yet, a lack of time has precluded an accurate determination of the plastic shock velocity, U_s . However, a value of 4.1 mm/ μ sec for U_s was obtained from two equation of state shots and was used to compute all pressures in this work. As a check, computed pressures were compared to an extrapolation of Walsh's data.²¹ The computed pressures did not deviate more than one kilobar from Walsh's. Plastic shock velocity is known to increase with pressure, but since the observed thresholds are within a 20 kilobar interval, the increase in shock velocity is negligible.

The same two equation of state shots gave the Hugoniot elastic limit or dynamic yield in compression of copper as about six or seven kilobars. Perhaps by coincidence, this is very close to the incipient spall threshold.

Approximate pulsewidths were obtained by dividing measured projectile plate thickness by the estimated shock velocity of 4.1 mm/ μ s.

Spall Velocity and Mass Loss

Velocities of a few spalled pieces were measured with a Fastax camera. Not enough measurements were made to establish a trend. The spalled pieces move with roughly 80 percent of the impacting plate velocity.

McQueen and Marsh⁵ speculate that sublimation may have caused the considerable mass loss in their high-pressure copper spall tests. In these low pressure tests, 1/2 to 3/4 percent mass loss is observed by weighing completely spalled samples. However the colored Fastax films show a copper colored cloud of fragments between the spalled piece and the remaining target. Hence, appreciable sublimation is unlikely at these low pressures.

Relative Spall Thickness

Thicknesses of detached spall pieces were determined by weighing while the unseparated ones were measured with a Filar eyepiece on the metallograph. Based on the data in Table II, the average projectile-to-spall thickness ratio is 1.03. The scatter of thickness ratios is probably caused mainly by inhomogeneities in the polycrystalline copper.

By making the assumption that the rarefaction also travels as a shock, a relation between the rarefaction-to-shock velocity ratio and the measured thicknesses may be derived. This relation, in conjunction with the data, indicates that the rarefaction exceeds the shock velocity by two or three percent. The detailed calculations are not presented because of the grossness of the treatment.

Conclusions

The experimental techniques discussed here for copper can be used to determine edge-effect-free spall thresholds in other metals and most nonmetals. The inherent control and accuracy of an air-gun facility exceeds that of a high-explosive facility, although the pressure range is limited with the former. Fortunately, most spall thresholds lie in this limited range.

*Report to be published by L. M. Barker and C. D. Lundergan of Sandia Corporation and Walter Herrmann of MIT.

Incipient spall occurs when the input pressure exceeds the compressive elastic limit. This could be indicative of a correspondence between the elastic limits in compression and tension. Also, the residual strength of samples tested between 16 and 22 kilobars is surprisingly constant.

Certain wave properties were important in this program. For example, spall damage depends on pulsewidth in addition to peak stress. And spall thickness measurements indicate that the rarefaction wave is a few percent faster than the shock front.

APPENDIX A

METALLURGY

Etching Techniques

The copper used in these experiments was specified as QQ-C-576, cold rolled, and 99.9 percent pure, plate stock. Actual hardness measurements gave averages of 93 on the Knoop scale and 68 on the Rockwell F scale. The density of this copper was 8.86 grams/cm.³

The 24 samples which the author sent to Dr. Herrmann at MIT had been chemically etched with ferric-chloride etchant. Unfortunately, rinsing in water and vibrating ultrasonically failed to remove all the etchant from the spall fractures. Consequently, the etchant may have continued its attack and lowered the residual strength of the samples.

A far superior method of etching, developed later and used on all incipient spall samples, is cathodic etching. Here, the spall sample is made the cathode of a four kilovolt gap in a chamber containing pure ionized argon. Finally, the positive ions of argon are allowed to bombard the sample for about two minutes. During the bombardment, the sample is in intimate contact with a heat sink to avoid deleterious effects caused by heating.

Bar vs Plate

All data reported in the tables are based on copper plate stock. Rolling the plate stock elongated and aligned the grains parallel to the subsequent spall plane. Hence the initial spall fractures tended to unite into larger voids.

Contrary to this tendency, the grains of copper bar stock of the same composition were aligned normal to the spall plane. This kept the initial spall fractures from tending to coalesce, thereby raising the spall thresholds. Only a few shots were fired with bar stock, but the meager data indicate that spall thresholds in bar stock would be only a few percent higher than in plate stock. See Figure A-1 for spall fracture in bar and plate stock.

**INTERMEDIATE SPALL
IN COPPER BAR**

**INTERMEDIATE SPALL
IN COPPER PLATE**

Figure A-1. Effect of Grain Alignment on Spall

APPENDIX B

SPALL PREVENTION

1-1/2 μ s Pulsewidth For This Test

One method¹⁹ for strengthening against spall is to diffuse either or both of the incoming and reflected waves by drilling conical holes in the target's impact or free surface or both. This wave diffusion causes spall to occur in a series of disconnected regions instead of a continuous plane. Thus, for a piece to separate, it must have enough momentum to shear the copper until all spall cracks are joined. Evidently this combination spalling and shearing process requires considerably more energy than simple spall. Figure B-1 illustrates how wave diffusion kept half a spall region connected at thirty-two kilobars, while the other half without wave diffusion spalled and separated as expected. Without wave diffusion, both sides of the spall region would have separated at about twenty-four kilobars with the grooved target.

Figure B-1. Spall Prevention by Wave Diffusion
(Impacted at 600 feet/second, 32 kb, 1.5 μ s square pulse, Cu on Cu)

L. M. Barker, a co-worker, suggested that the holes might give an apparent increase in strength simply by reducing the mass of the spall piece. Thus the spall piece might not break free because of its reduced momentum. However, the reduction of mass proved to be a minor effect. The holes in the eighth-inch thick copper spall piece, shown below, reduced its momentum by eight percent. But increasing the pressure from twenty-four to thirty-two kilobars increases the spall piece's momentum by about thirty percent. Therefore, we have a net gain in strength of twenty-two percent and still it did not spall. Hence, the strengthening against spall by wave diffusion is much more significant than a simple reduction of mass.

APPENDIX C
MISCELLANEOUS FIGURES

Figure C-1. Miscellaneous Spall Samples

Legend:

U = Material Velocity
 P = Pressure
 t = Time

Figure C-2. Wave Diagram of a Single Shock Wave Produced by Impact of Two Plates of the Same Material

Figure C-3. Diagram of Portion of Air Gun

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