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TESTING CHROMIUM ADHESION USING ACOUSTIC EMISSION

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The use of acoustic emission was investigated as a method of characterizing chromium adhesion on steel. The samples used in the study were cylinders cut from the muzzle end of 120-mm gun tubes, plated on the inner surface with chromium, and cut to form split rings. Acoustic emission data was taken during loading of each ring. The results of the study are inconclusive regarding the effectiveness of acoustic emission as a test method for chromium adhesion.

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INTRODUCTION

The purpose of this study was to investigate a method of characterizing the strength of chromium adhesion on steel using acoustic emission (AE). Because AE techniques have proven useful in detecting and identifying various failure mechanisms in metals and composites, we felt that these techniques could also be used to detect adhesive failure of chromium (delamination) and to distinguish it from other mechanisms that might occur during testing, such as crack initiation and propagation.

EXPERIMENTAL DETAILS

The samples used in the study were 1-inch thick cylinders cut from the muzzle of 120-mm gun tubes prior to plating. Each section was then plated on its inner surface with high contraction (HC) chromium while being held in contact with the remaining gun tube. Afterward, a 1-inch wide piece was removed for use in groove testing, leaving a split-ring specimen as shown in Figure 1. The thickness of the chromium coating at the inner radius was between 0.050 and 0.125 mm.

In order to characterize the acoustic emission due to delamination, it was first necessary to devise a method of causing delamination with a minimum of extraneous acoustic noise. The method chosen was to pull the ring apart, as shown in Figure 1, using a load controller (Instron model 1350). This method of loading the ring resulted in a high tensile stress at the inner diameter in the region opposite the split. Using linear elasticity theory (ref 1), the nonzero stress components were found to depend on radial position r and angle θ in the following manner:

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[1] R. V. Southwell, An Introduction to the Theory of Elasticity for Engineers and Physicists, Second Edition, Oxford, 1941.

$$\sigma_{\theta\theta} = \frac{F\cos\theta/D}{\ln(b/a) - \left(\frac{b^2-a^2}{b^2+a^2}\right)}\left[\frac{a^2b^2}{(a^2+b^2)r^3} - \frac{3r}{a^2+b^2} + \frac{1}{r}\right]$$

$$- \frac{4aF/D}{b^2-a^2 - \frac{[2ab\ln(b/a)]^2}{b^2-a^2}}\left[1 + \frac{(b/a)^2\ln(r/b) - \ln(r/a) - (b/r)^2\ln(b/a)}{(b/a)^2 - 1}\right] \qquad (1a)$$

$$\sigma_{rr} = \frac{F\cos\theta/D}{\ln(b/a) - \left(\frac{b^2-a^2}{b^2+a^2}\right)}\left[- \frac{a^2b^2}{(a^2+b^2)r^3} - \frac{r}{a^2+b^2} + \frac{1}{r}\right]$$

$$- \frac{4aF/D}{b^2-a^2 - \frac{[2ab\ln(b/a)]^2}{b^2-a^2}}\left[\frac{(b/a)^2\ln(r/b) - \ln(r/a) + (b/r)^2\ln(b/a)}{(b/a)^2 - 1}\right] \qquad (1b)$$

$$\sigma_{r\theta} = \frac{F\sin\theta/D}{\ln(b/a) - \left(\frac{b^2-a^2}{b^2+a^2}\right)}\left[- \frac{a^2b^2}{(a^2+b^2)r^3} - \frac{r}{a^2+b^2} + \frac{1}{r}\right] \qquad (1c)$$

F is the force opening the ring at the split, D is the thickness of the ring in the axial direction, and a and b are the inner and outer radii, respectively. These equations, of course, are only valid for elastic deformations.

At the inner radius (r=a), both σ_{rr} and $\sigma_{r\theta}$ vanish, leaving the chromium coating essentially stressed in one direction. For the dimensions of our specimens, a = 2.36 inches, b = 2.99 inches, and D = 1 inch, the stress at the inner radius becomes

$$\sigma_{\theta\theta}\Big|_{r=a} = 45.6\ F\cos\theta/\text{in.}^2 \qquad (2)$$

We chose to load the chromium coating in tension because of the simplicity of doing so and because the resulting stress can cause adhesive failure of the coating as a normal rupture crack in the chromium approaches the chromium-steel interface (refs 2-4). In addition to the expected tensile stress perpendicular to the crack, there is a region ahead of the crack tip containing a high tensile stress parallel to the crack (refs 3,4). This is true both in a homogeneous material and near the interface between two bonded materials. Consequently, the sort of loading situation shown in Figure 1 would likely lead to both propagation of cracks in the chromium and separation of chromium from the steel substrate. Such behavior of a chromium coating on steel has already been observed in a similar loading situation (ref 2).

Acoustic emission activity was observed during each test using standard commercial equipment consisting of three resonant piezoelectric transducers (150 kHz, sensitivity of -70 dB re 1 V/microbar, Physical Acoustics Corp. model R15); preamplifiers with 40 dB gains (Physical Acoustics Corp. model 1220A); amplifier and analyzer (Physical Acoustics Corp. model 3104); and computer (Physical Acoustics Corp. model 3000). The transducers were acoustically coupled to the specimen surface with silicone grease.

An experiment usually consisted of varying the loading displacement, rather than force, linearly with time at a rather slow rate and observing the resulting acoustic emission activity. The loading rate was typically between 0.036 and 0.12 in./min. Because we expected the majority of relevant signals to emanate from the region of high stress opposite the split, the top and bottom transducers were used as guard sensors. That is, any AE event that reached either

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[2] A. F. Shurov, A. M. Shiryaev, A. M. Kotkis, B. A. Zelenov, I. D. Efros, and I. E. Leontovich, "Method of Measurement of the Strength and Adhesion of Metallic Coatings Applied to the Inner Surface of Tubular Specimens," Industrial Laboratory, Vol. 51, 1985, p. 672; translated from Zavodskaya Laboratoriya, Vol. 51, No. 7, 1985, p. 82.

[3] J. Cook and J. E. Gordon, "A Mechanism for the Control of Crack Propagation in All-Brittle Systems," Proc. Roy. Soc. London, Series A, Vol. 282, 1964, p. 508.

[4] A. R. Zak and M. L. Williams, "Crack Point Stress Singularities at a Bi-Material Interface," J. Applied Mechanics, Vol. 30, March 1963, p. 142.

one of these transducers first was automatically discarded by the analyzer. This helped to eliminate acoustic noise from the load controller and holders.

In most tests, the waveform for each detected AE event was automatically analyzed and a limited number of parameters for each event was recorded; the waveform itself was normally not saved. The parameters recorded included time, amplitude, counts, energy, duration, and rise time. In a few tests, event waveforms were digitized using an A/D converter and stored for subsequent frequency analysis. For each event, 256 points at intervals of 1 microsecond were digitized with an 8-bit resolution. The frequency analysis was performed using the fast Fourier transform algorithm after truncating the waveform with a Hamming window to reduce leakage (ref 5).

RESULTS

As the load was increased, all the specimens showed a region of little or no AE activity followed by a rapid onset of vigorous activity that eventually died down as the load continued rising. This sort of behavior is illustrated in the first rise of Figure 2, a plot of cumulative counts versus increase in ring opening. The lower amplitude distribution in Figure 3 is typical of the amplitude distributions for this AE activity. Although the true distribution actually extends to lower amplitudes, the threshold setting of the analyzer had eliminated the lower amplitude signals. Metallographic examination of several specimens after this period of AE activity revealed a large number of cracks that had propagated to the chromium-steel interface, as shown in Figure 4. No delamination of the chromium was observed for these specimens.

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[5] E. O. Brigham, The Fast Fourier Transform, Prentice-Hall, New Jersey, 1974.

In addition, several specimens showed a second region of AE activity as the load continued to increase, shown in the second rise of Figure 2. The higher amplitude distribution in Figure 3 characterizes such AE activity. Visual and metallographic examinations of these specimens after this period of AE activity reveal that chromium has actually separated from the substrate steel in many places, as shown by the photograph in Figure 5.

From these observations, it is reasonable to conclude that the first period of AE activity is due to the propagation of cracks in the chromium. This AE activity eventually dies down with increasing load probably because the existing cracks reach the chromium-steel interface and cease propagating. The second region of observed AE activity can be attributed to delamination, the breaking of bonds near or at the chromium-steel interface.

As Figure 3 shows, the amplitude distributions for these two distinct AE mechanisms are quite different. The chief distinguishing feature is that the distribution of signals from crack propagation is broad and falls off with increasing amplitude, whereas the distribution of signals from delamination tends to be narrow and at a higher amplitude.

Attempts to find other features that distinguish delamination events from cracking events have not been successful. These have included an attempt to detect differences in frequency content by examining the Fourier transform of digitized waveforms. However, no significant difference in the frequency content between signals from crack propagation and those from chromium delamination was observed.

It seems logical to suspect that the load at which delamination of the chromium occurs would be a useful comparative measure of the strength of adhesion, at least for the specimens that showed delamination. With this possibility in mind, we compared the loading displacement that caused delamination with the amount of chromium lost in firing tests on the corresponding gun tubes. The firing test data used was the amount of surface area in zone 5 that showed loss of chromium after three rounds were fired. The data, summarized in Table I, does not suggest any significant correlation.

We also examined the possibility that there might be a correlation between the load that caused crack propagation and the chromium loss from firing tests. Again, however, no correlation was observed.

CONCLUSION

The lack of correlation between our measurements and the results of firing tests does not necessarily invalidate our method of characterizing chromium adhesion. The chromium that came off during firing of the gun tubes represents an extremely small fraction of the chromium in zone 5. The area of chromium tested in our split-ring specimen was also quite small; it is unlikely that such a small sample would include chromium that would have come off had it been subjected to the stress of firing.

REFERENCES

1. R. V. Southwell, An Introduction to the Theory of Elasticity for Engineers and Physicists, Second Edition, Oxford, 1941.
2. A. F. Shurov, A. M. Shiryaev, A. M. Kotkis, B. A. Zelenov, I. D. Efros, and I. E. Leontovich, "Method of Measurement of the Strength and Adhesion of Metallic Coatings Applied to the Inner Surface of Tubular Specimens," Industrial Laboratory, Vol. 51, 1985, p. 672; translated from Zavodskaya Laboratoriya, Vol. 51, No. 7, 1985, p. 82.
3. J. Cook and J. E. Gordon, "A Mechanism for the Control of Crack Propagation in All-Brittle Systems," Proc. Roy. Soc. London, Series A, Vol. 282, 1964, p. 508.
4. A. R. Zak and M. L. Williams, "Crack Point Stress Singularities at a Bi-Material Interface," J. Applied Mechanics, Vol. 30, March 1963, p. 142.
5. E. O. Brigham, The Fast Fourier Transform, Prentice-Hall, New Jersey, 1974.

TABLE I. COMPARISON OF FIRING TEST RESULTS AND ACOUSTIC EMISSION RESULTS

Tube Number	Third Round Chromium Loss (mm^2)	Cracking Load (in.)	Delamination Load (in.)*
249		0.128	1.888
330	70	0.144	2.424
340	646	0.176	>3.68
365	587	0.172	>3.62
384	146	0.172	>3.66
385	329	0.132	>3.66
386	139	0.172	2.692
388	142	0.02	>3.59
389	138	0.212	>3.66
394	159	0.136	>3.62
420	74	0.352	>3.64
484	363	0.188	>3.63
512	18	0.16	>3.60
538	170	0.156	>3.64
569	6961	0.14	1.74
601	39	0.168	>3.67
659		0.244	1.844
731	83	0.22	2.42
777	31	0.112	>3.61
1368		0.208	1.608

*The symbol ">" next to the delamination load means that the sample was loaded up to this value, yet did not experience delamination.

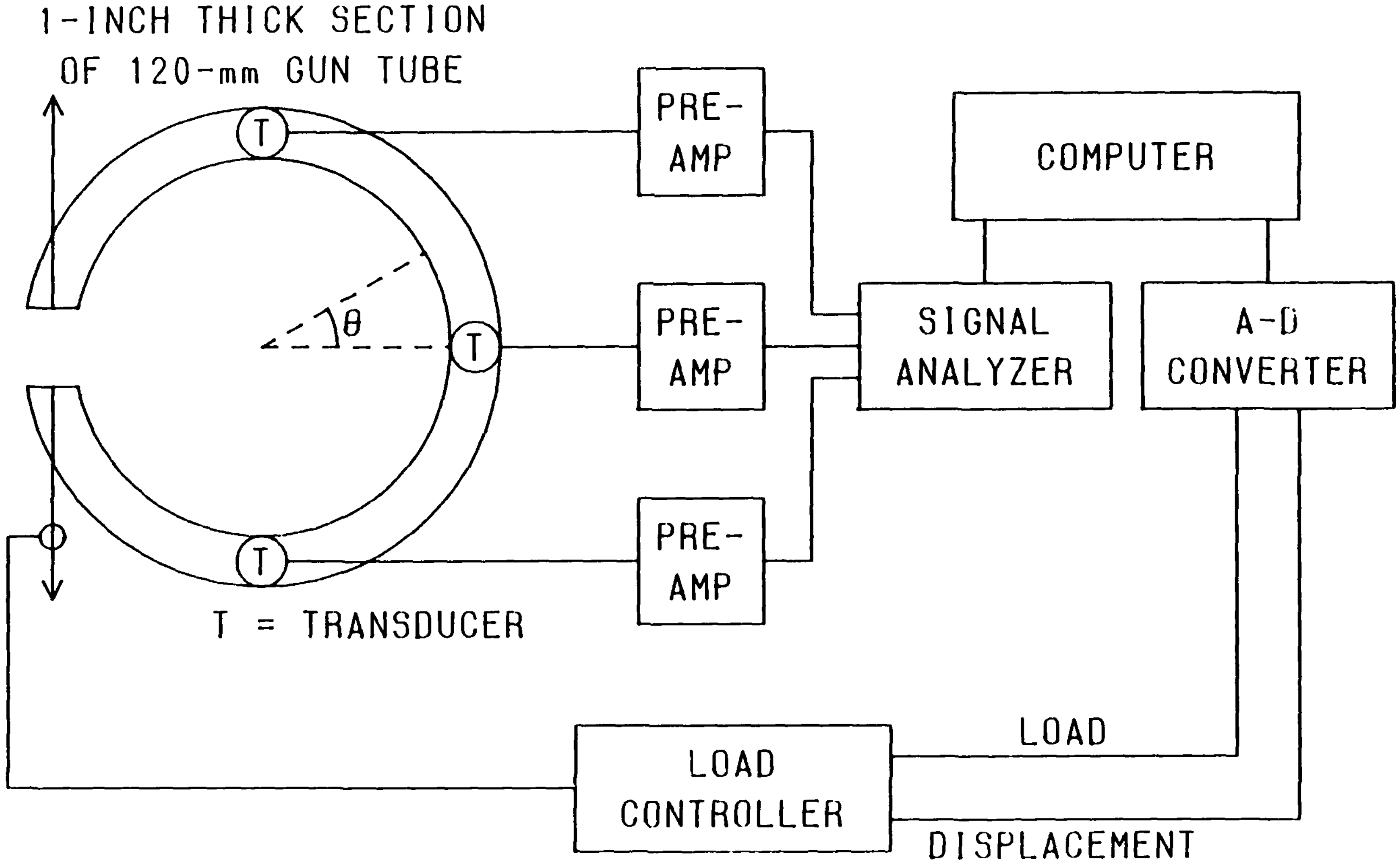

Figure 1. Schematic of acoustic emission experiment.

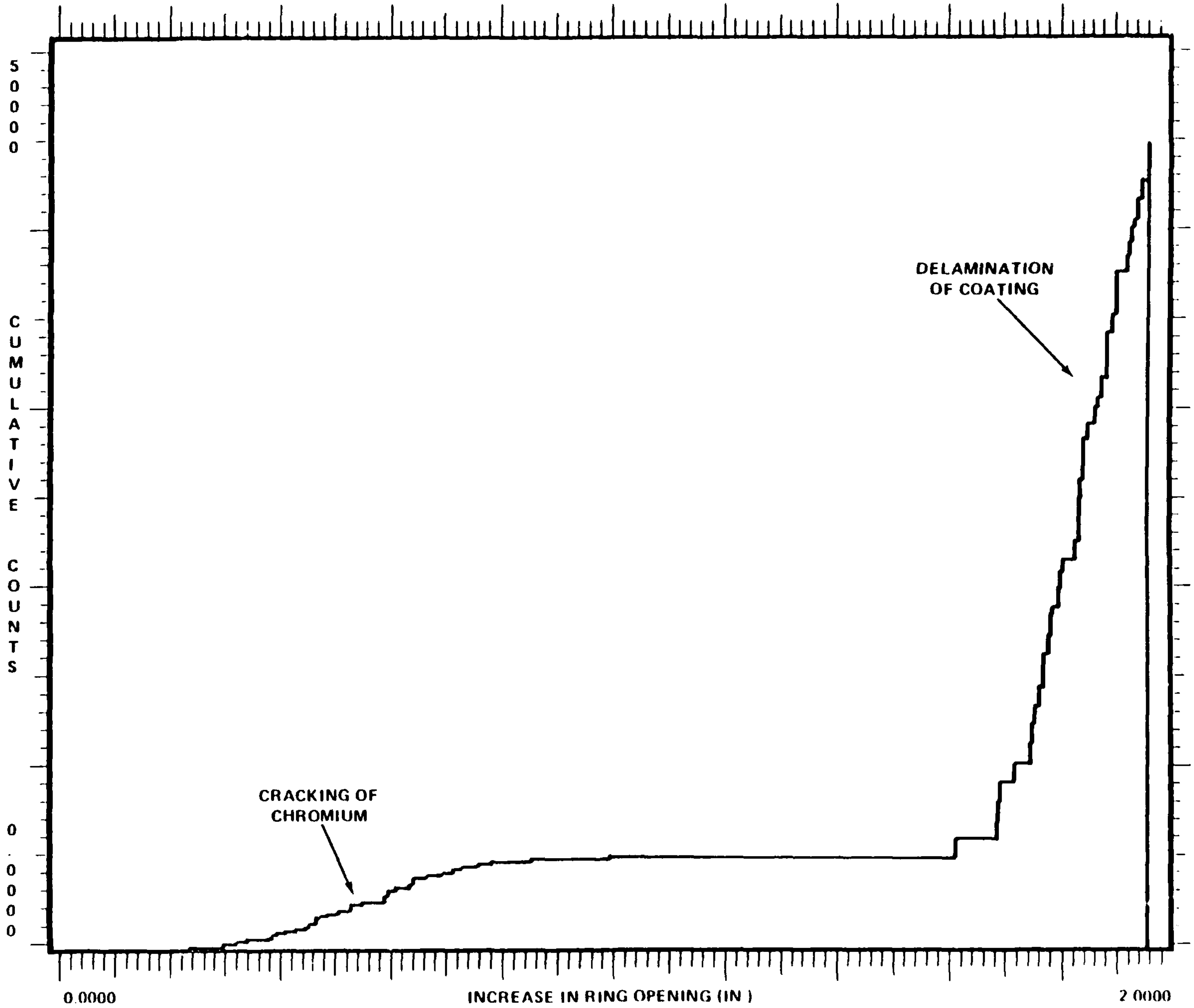

Figure 2. Cumulative AE counts versus increase in ring opening.

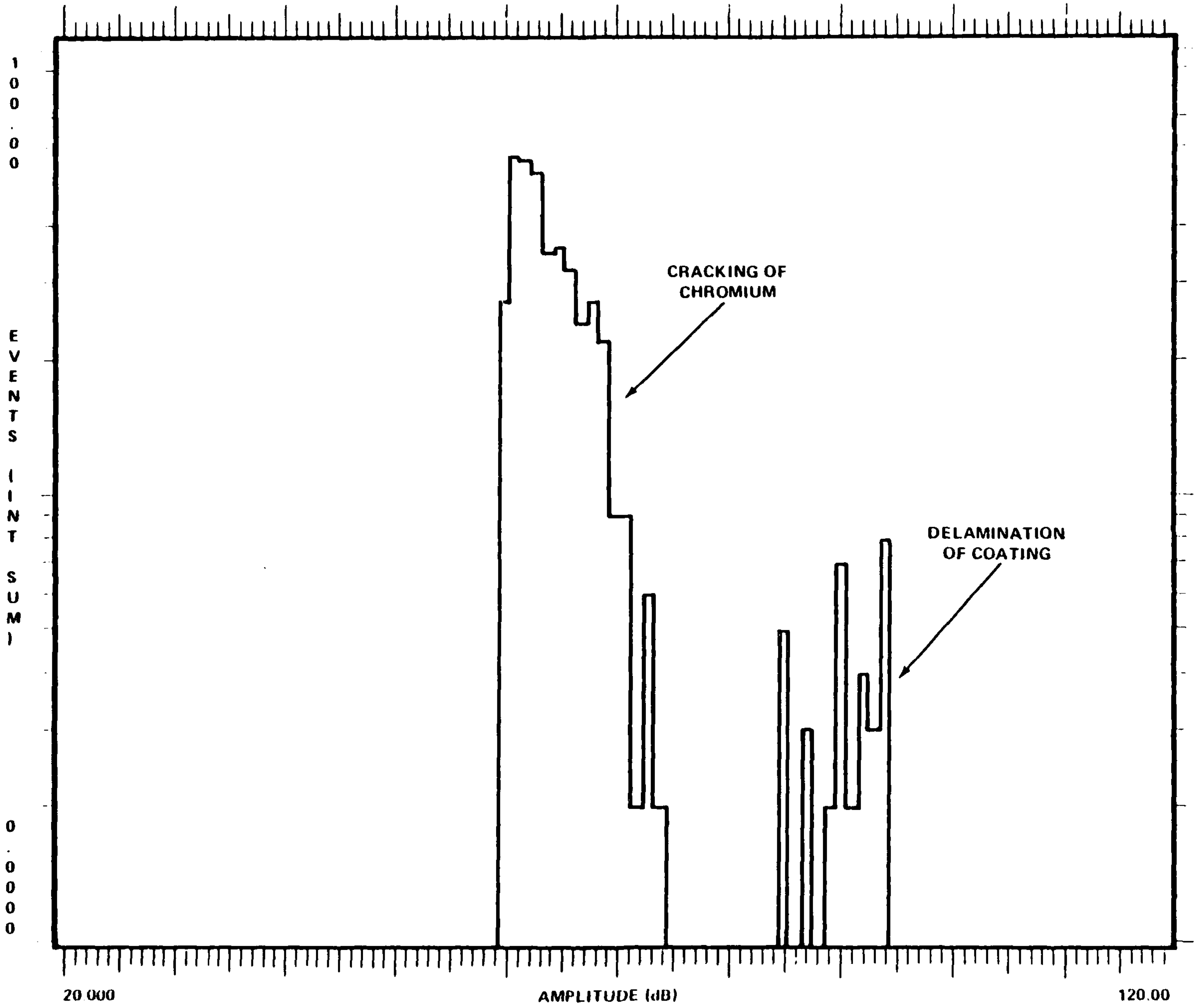

Figure 3. Typical AE amplitude distribution showing cracking and delamination.

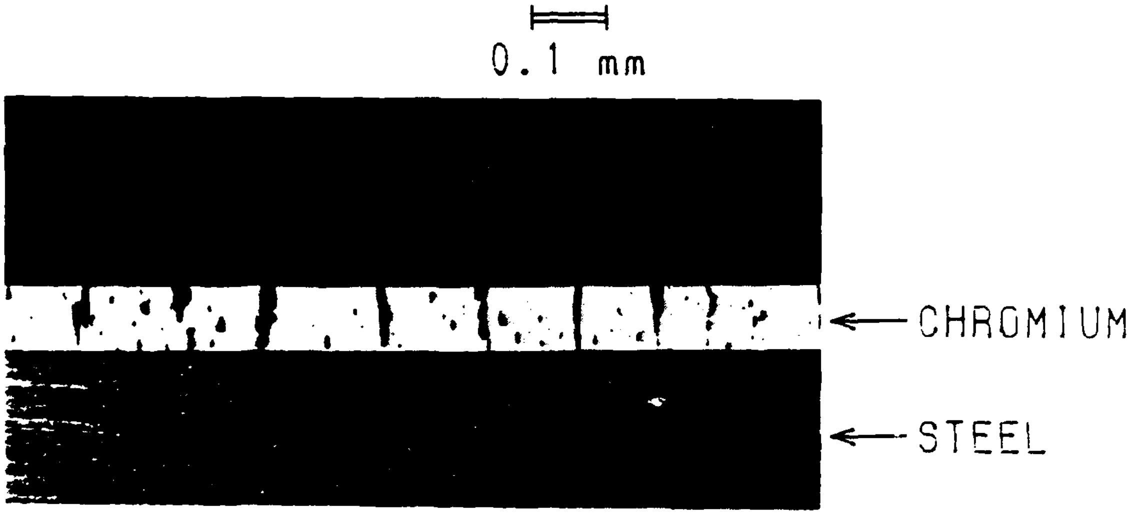

Figure 4. Cracked chromium.

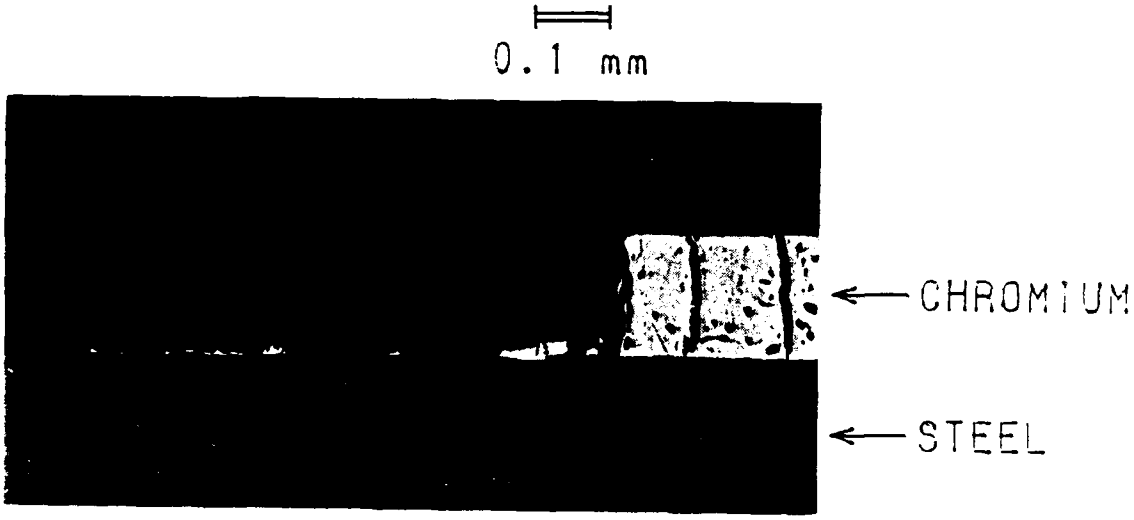

Figure 5. Delaminated chromium.

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