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Acuff, James T.

Rensselaer Polytechnic Institute

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James T. Acuff and
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By

James T. Acuff, B.S., B.C.E.

and

Robert J. Farley, B.S., B.C.E.

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OBJECT

The object of this investigation is to determine the possibility of measuring quantitatively the residual stresses in metal plates by means of brittle lacquer. It is known that the residual stresses can be determined qualitatively by use of the brittle lacquer from the work of previous investigators. This investigation will concern itself with correlating the size of the pattern formed in the lacquer on the release of the residual stresses with the actual value of the residual stresses in the metal.

IMPORTANCE

There is a great need for a simple yet accurate method for determining the residual stresses in a member without actually destroying the member or the structure containing the member. If it were possible to determine the magnitude of the stresses by the use of brittle lacquer, the simple and inexpensive method needed would have been found. The work of previous investigators has shown that the presence and type of residual stresses can be found by the use of brittle lacquer. In order to be of greatest use, however, the quantity of stresses present should be known. The brittle lacquer could then be used as a method of testing a member after it has been placed in a structure.

It is known that a member containing residual stresses will yield under a smaller load than a member free from residual stresses. If each structural member could be designed as if free of residual stresses, the weight of steel necessary would be greatly reduced. Naturally, no structure could be built without inducing residual stresses, but the amount of stresses could be greatly reduced by proper sequence of construction or other precautions. The members could be tested after erection to see if they conformed to the design specifications.

PROBLEM

The investigation resolved itself into the following problem: To correlate the patterns formed by drilling a small hole in a lacquer-coated metal piece as described in references "A" and "B" with the values of the residual strains found by some other method. It was decided to measure these residual strains by placing a wire strain gage on the metal sample which contained residual stresses and then cutting the gage away. The corrected difference between the Strain Indicator reading before and after the cutting would be the value of the residual strain.

THEORY

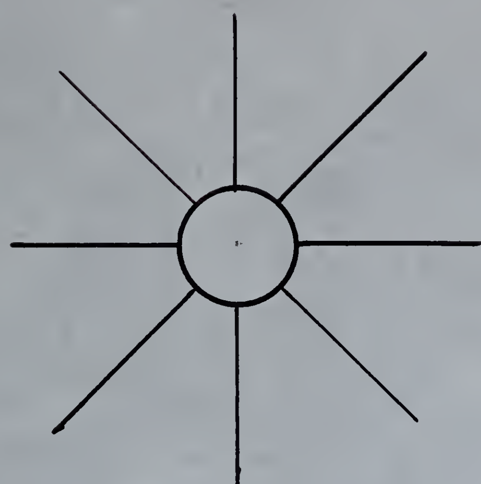
The formation of the strain patterns is the result of drilling a hole in the metal. In the case of residual tension, the relief of the strain allows the metal to contract and radial cracks are formed. Whereas, with the relief of compressive forces, the metal expands and attempts to fill the hole causing circular cracks to form concentric to the hole. These theoretical patterns are shown on Plate I.

The same thing would happen when the strain gages are cut out. Relief of tensile strains would cause the metal to contract and compressive strains, when relieved, would cause the metal to expand. The gages when cut away measure 1.8" x .45"; thus the difference in the readings of the gage is actually (.45 - 1.8u) x the actual residual strain in the piece.

Since the amount of metal effected increases as the square of the distance from the hole increases, the length of the crack should increase as the square of the residual strain. Also, the larger the hole made, the greater the quantity of strain relieved. The quantity of strain will vary with the diameter of the hole. Therefore, in plotting the results, the square root of the length of the crack divided by the diameter of the hole was plotted against the residual strain.

PLATE I

COMPRESSION



TENSION

THEORETICAL PATTERNS

PROCEDURE

General

The procedure followed in this investigation was that recommended by the Magnaflux Corporation, manufacturers of Stresscoat. This procedure was as follows:

1. Spray test sample with brittle lacquer.
2. Drill small hole into test piece.
3. Apply dye etchant to lacquer.
4. Investigate pattern of residual stress present in the test sample at the place of the hole.

In the following investigation it was endeavored to determine the amount of residual strain present by measuring the size of the pattern formed in the brittle lacquer with the release of the residual strain. In order to obtain a high sensitivity a lacquer two or three numbers above that recommended by the Magnaflux Corporation was used. The samples were dried for 24 hours in an oven at 100 to 110 degrees F. in order to prevent crazing.

The procedure used to determine the actual residual strain was as follows:

1. Cement electric strain gage, type SR4a, as close to the hole as practicable.
2. Obtain initial strain reading.

3. Cut the strain gage from the sample.
4. Obtain final strain reading and determine the value of the residual strain.

The results were then plotted on Plate II.

HISTORY OF THE EXPERIMENT

In order to obtain high residual strains which would be fairly uniform throughout the sample, it was decided to use a heat-treatable steel as our test sample. SAE 8630 steel was selected for this purpose. The samples were cut from a normalized strip of steel and measured 10" x 2" x 1/16". A sample 1/8" thick or thicker would have been better for this purpose because less distortion would have occurred when it was quenched. The samples were soaked for thirty minutes at 1500 degrees F. Some were then quenched in water and some in oil to obtain different hardness values and, therefore, different strain values. The samples were then tested for ease of drilling. The water-quenched samples were too hard to drill with either plain carbon or high speed drills, but they could be drilled with a specially treated plain carbon drill. This treatment of the drill consisted of heating for fifteen minutes at 1500 degrees F. and quenching it into mercury. The above treatment produced a very hard but very brittle drill. The oil-quenched samples could be drilled with high speed drills. It was decided to discard the water-quenched samples and to concentrate on the oil-quenched samples because the specially treated drills were too brittle for continuous use.

A large number of pieces were then heat-treated and sprayed. Using a number 40 high speed drill, several holes were drilled in each sample. Patterns were observed and measured in most of the pieces. The best patterns were photographed. Examples of the patterns are shown in the photographs included as part of this thesis.

SR4a wire strain gages, type A-1, were placed on the pieces near the holes showing the patterns. Initial readings were taken on the gages and then, using shears, the gages were cut out of the sample. Again readings were taken on the gages and the values of residual strains were computed. Comparison of the residual strains with the length of cracks in the brittle lacquer showed erratic results.

After examination of the test results, it was decided that the method of cutting the gages out of the pieces was introducing excessive additional strain in the samples. Therefore, a test was carried out to find the magnitude of the strains induced in the samples by three different methods of cutting; namely, the shears, the power hack saw, and the hand hacksaw. A fourth method, the use of a water-cooled cutting wheel, was discarded after consultation with Mr. Walter Koonradt, Metallurgy and Welding Department, Rensselaer Polytechnic Institute. He advised that the wheel could not be adjusted accurately enough to cut closely to the strain gage and that the vibration from the wheel would tend to loosen the gage on the sample. The test for the first three methods consisted of placing three strain gages on normalized samples and then cutting them away by the various methods. The shears induced strains to the order of 1000 micro-inches; the power hacksaw 100 micro-inches; and the hand hacksaw 50 micro-inches. On the basis of this test, it was decided to use the hand hacksaw for cutting out the strain gages. However, it was almost impossible to cut the treated steel with either the hand or the power hack saws. At this point, it was apparent that cutting away electric strain gages to find the residual strain was not satisfactory for use with a material such as steel or any other material which has high hardness accompanying the high residual strains necessary for this investigation.

Aluminum, which can be made to have high residual strains without high hardness, was selected for the next tests. The samples were pieces of 24S-0 Aluminum 2" x 6" x 1/8" which were heat-treated for thirty minutes at 925 degrees F. and quenched in cold water. Twenty pieces were sprayed and then tested by drilling holes with a 3/32" drill. Patterns were observed on only two pieces. Gages were placed near the holes where patterns were present and strain readings were taken. The gages were then cut out of the samples by a hand hacksaw and strain readings were taken again. Because of the small number of pattern formations observed, it was decided to cold-work the next group of aluminum samples. The samples were cold-rolled with a maximum reduction of 60%. The spraying procedure was repeated on these samples and the holes drilled with a 3/32" drill. No patterns were observed. Gages were placed on several of the pieces to find the actual residual strains present in order to determine the threshold sensitivity of the brittle lacquer method. These gages were cut away and the strains recorded.

Dowmetal was the third metal tried for this experiment. Twenty samples, reduced 15% by cold-rolling, were sprayed and drilled. In two of these pieces, patterns were observed. These were the first compressive cracks found in this investigation. Although the patterns were not well enough defined to photograph, the cracks and the residual strains were measured and recorded in the usual manner.

Due to the lack of time, it was impossible to attempt any further investigations. However, it is felt that there is sufficient justification for further tests. Accurate conclusions should be obtained with an improved method of finding the actual residual strains.

RESULTS

The results of the tests are tabulated in Table I. There are some glaring inconsistencies in the relationship between the size of the patterns and the measured residual strains. In the case of the steel specimens, one gage (gage 5) showed a compressive residual strain, but all of the patterns observed on the steel samples were tensile patterns. Also, on the Dowmetal samples, which showed all compressive patterns, gage 23 gave a tensile reading. All of the data obtained from the steel samples must be considered worthless because of the unpredictable high shearing stresses induced as a result of the method used in removing the gages from the samples. There is not sufficient date from the lighter metals to form a definite conclusion.

The findings from the aluminum and Dowmetal tests are plotted on Plate II. They show nothing conclusive inasmuch as they are too few in number and are quite dispersed. The residual strains found in the pieces in which no pattern resulted were quite high and cast some doubt on the validity of the brittle coating method even as a qualitative indicator.

TABLE I

Group	Piece	Hole	Length of Line	Gage	Reading Before	Reading After
	1	No results				
	2	No results				
	3	1	.09	1	5-1795	7-1794
		2	.10			
		3	.06	2	5-1030	
		4	.08			
		5	--	3	5-0801	7-0949
		6	.08			
	4	1	.18	4	5-1838	9-0801
		2	.10			
		3	.09	5	6-1228	4-1519
		4	.09	6	6-1419	
		5	.10			
		6	.13	7	6-1579	9-0977
		7	.13			
A	1	No results				
	2		.04	12	5-0885	5-1489
				13	6-0758	8-1599
	3		.08	14	7-1075	8-1090
				15	4-1134	5-1155
	4		.09	16	6-1019	8-1121
				17	6-1083	6-1725
	5	No results				

Diff.	f=(.45 -1.8u)	Strain= diff./f	Drill size	$\left(\frac{\text{Length}}{\text{dia.}}\right)^{1/2}$
1999	-.26	-7680	.098	.306
2148	-.26	-8260	.098	.288
2913	-.26	-11,200	.098	.433
-1709	-.26	6560	.098	.306
2398	-.26	-9210	.098	.367
604	-.26	-2320	.098	.202
2841	-.26	-10,930	.098	
1016	-.26	-3905	.098	.238
1021	-.26	-3930	.098	
2102	-.26	-8100	.098	.306
642	-.26	-2470	.098	

TABLE I (cont'd)

Group	Piece	Hole	Length of Line	Gage	Reading Before	Reading After
	6	No results				
	7	No results				
	8		.07	10	5-0348	6-1258
				11	6-0734	5-1806
	9	No results				
	10		.10	8	5-0947	6-0290
				9	5-1028	6-0643
I	I_1	3	.23	18	6-0992	6-1020
				19	4-1201	4-1149
	I_2	2	.20	20	6-0368	5-0738
		3	.21	21	6-1151	7-0862
L	L_1	1	.45	22	7-0801	7-0290
		2	.30	23	7-1167	8-0501
	L_2	1	.25	24	5-1955	5-1216
		3	.15	25	6-1080	6-0870
	JH				5-1121	6-0919
	JE				7-1110	8-0411
	JW				7-1650	8-0600
	JK_1				7-1670	7-1607
	JK_2				7-0930	6-1765
	JF				6-1061	5-1525

Diff.	f=(.45 -1.8u)	Strain= diff./f	Drill size	$\left(\frac{\text{Length}}{\text{dia.}}\right)^{1/2}$
1910	-.26	-7350	.098	.270
72	-.26	-277	.098	
337	-.26	-1295	.098	.332
615	-.26	-2365	.098	
28	-.24	-107	.014	.490
-52	-.24	216	.094	
-630	-.24	2620	.094	.457
711	-.24	-2960	.094	.470
-611	-.26	2350	.094	.683
434	-.26	-1670	.094	.558
-737	-.26	2840	.094	.510
-210	-.26	809	.094	.395
798	-.24	-3320		
301	-.24	-1250		
-50	-.24	208		
-63	-.24	262		
-165	-.24	687		
-436	-.24	1818		

TABLE II

TREATMENT OF THE SAMPLES

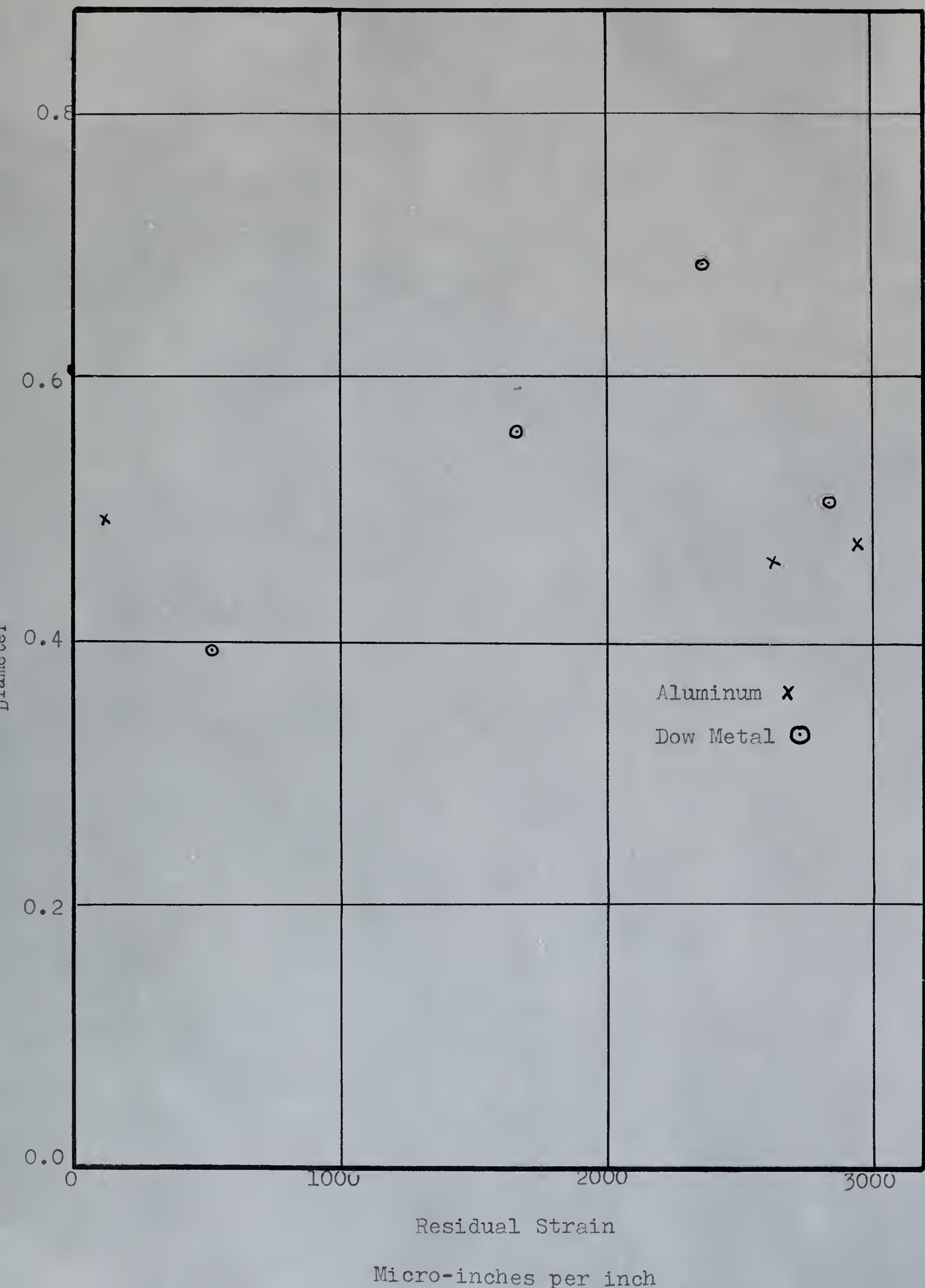
SAMPLE		METHOD OF TREATMENT
	8630 Steel	
1		Heated to 1500 degrees F. Held for 30 min. at temperature. Quenched into oil.
2		Same as No. 1.
3		Same as No. 1.
4		Same as No. 1.
Group A		Same as No. 1.
	24S-O Aluminum	
Group I		Heated to 925 degrees F. Held for 30 min. at temperature. Quenched into cold water.
Group JH		Cold reduced 48%
Group JE		Cold reduced 51%
Group JK		Cold reduced 62%
Group JW		Cold reduced 36%
Group JP		Cold reduced 43%
	Dowmetal	
Group L		Cold reduced 15%

TABLE III

POISSONS RATIO:

8630 Steel	0.34
Aluminum	0.33
Dowmetal	0.34

PLATE II


0.8
0.6
0.4
0.2
0.0
0
1000
2000
3000
Aluminum X
Dow Metal ⊙
Residual Strain
Micro-inches per inch

CONCLUSIONS OF THE INVESTIGATION

The results of these experiments with the brittle lacquer as a measure of residual stresses yielded no definite results as far as quantitative measurements are concerned for one of the following reasons: Either the brittle lacquer method is of little value in estimating stresses, or the method used to find the residual strains is not satisfactory. It is the opinion of the authors that the latter reason is the chief cause of the indefinite results obtained. However, inability of the lacquer to show strain patterns on the greatly reduced aluminum samples has led the authors to look upon the brittle lacquer method with caution even as a qualitative indicator of residual strains. In the use of the electric strain gages there is always the uncertainty as to the magnitude of the strains induced by cutting away the gage. For this reason, it is felt that some other method of finding the residual strains should be employed before a definite decision can be reached as to the value of the brittle lacquer method for quantitative measurement of residual strains.

There are two other procedures which could be used to measure the residual strains. One method is the use of X-ray techniques and the other method is the use of high temperature strain gages. The first method is outlined in reference "G". Since this method involves much expensive equipment and study in the operation of the equipment, it was not readily available for use in this investigation. The second method has greater possibilities. The construction, use, and calibration of these high temperature gages are outlined in reference "D". The procedure to be followed if this latter method were to be used would be to place the high temperature strain gage on the sample in its condition of high residual strain. Then place the piece in a furnace at an elevated temperature in order to relieve the stresses in the piece as described in reference "I". Since the gage could withstand the high temperature involved, a comparison of the resistance readings of the gage before and after stress relief would measure the residual strains. This method should be especially accurate as it involves no additional strain due to cutting. However, there is one serious obstacle to the use of this method which must be overcome; that is the long baking period totaling 32 hours at 250 degrees F. which is specified after placing the gages on the sample. It should be possible to place the gages on the sample without resorting to such high temperature baking. This drying period undoubtedly would contribute considerable stress relief. Perhaps a longer drying period at room temperature would suffice. If a solution to this problem could be found, the measurement of residual strains could be easily accomplished.

During the course of the experiments it was noted that cracks of varying intensities were formed with approximately the same length. Some of the patterns formed were considered to be crazing. However, other investigators identified these patterns as strain indications as illustrated in references "A" and "B". The patterns shown in the pictures taken of some of the plates in the authors' experiments are not of this character. The authors feel that there should be some distinction made between the strong patterns and the weak ones. As they were unable to get any satisfactory results due to the difficulties in measuring the residual strains with the SR4a strain gages, it was impossible to make the proper comparison.

The authors feel that more work is warranted on this topic because the brittle lacquer method of stress analysis is a simple, yet effective, system.

If it can be proven that the brittle lacquer method is valuable in measuring quantitatively the residual strains in metal, a very worthwhile tool will be open for use by the stress analyzer.

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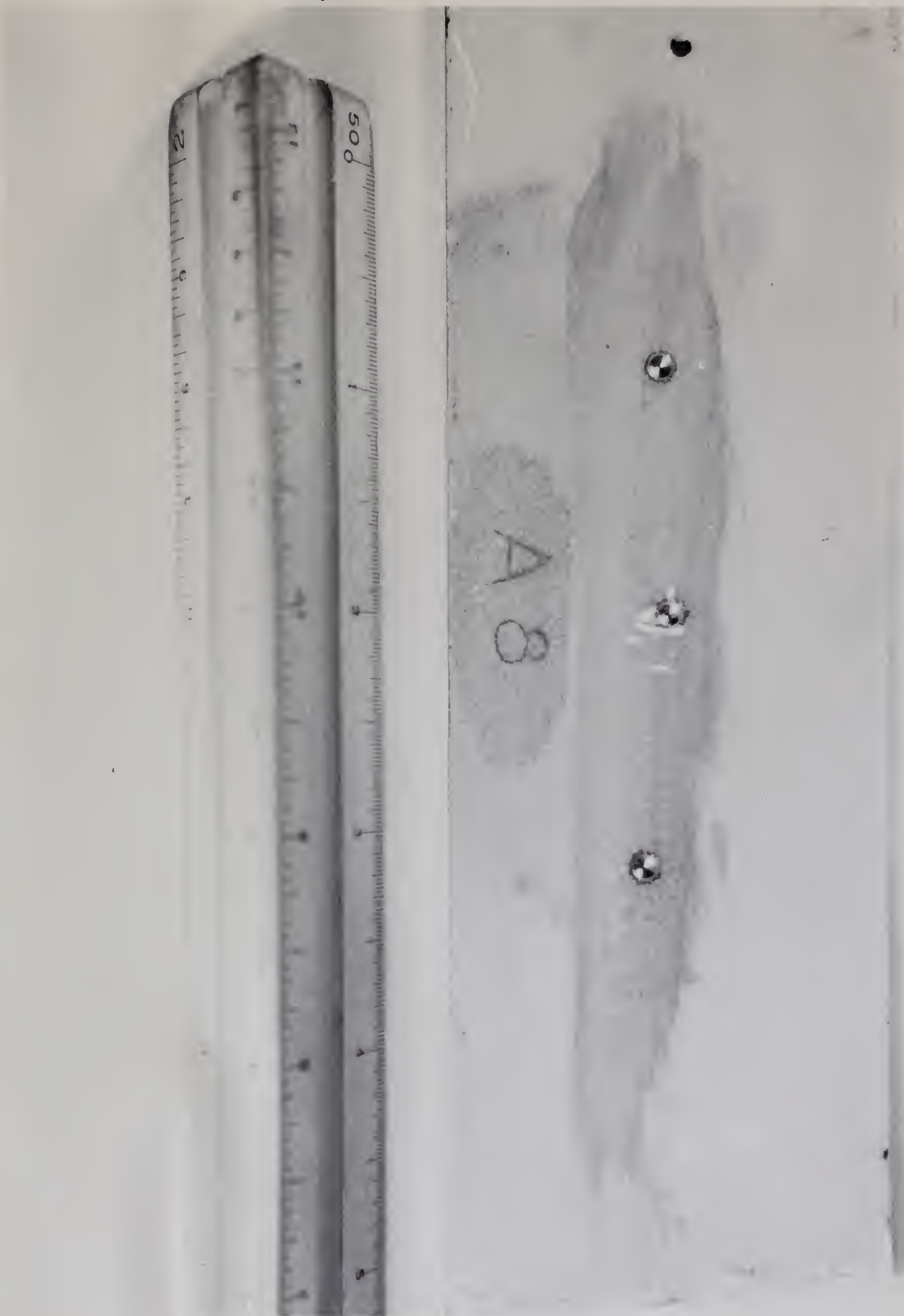
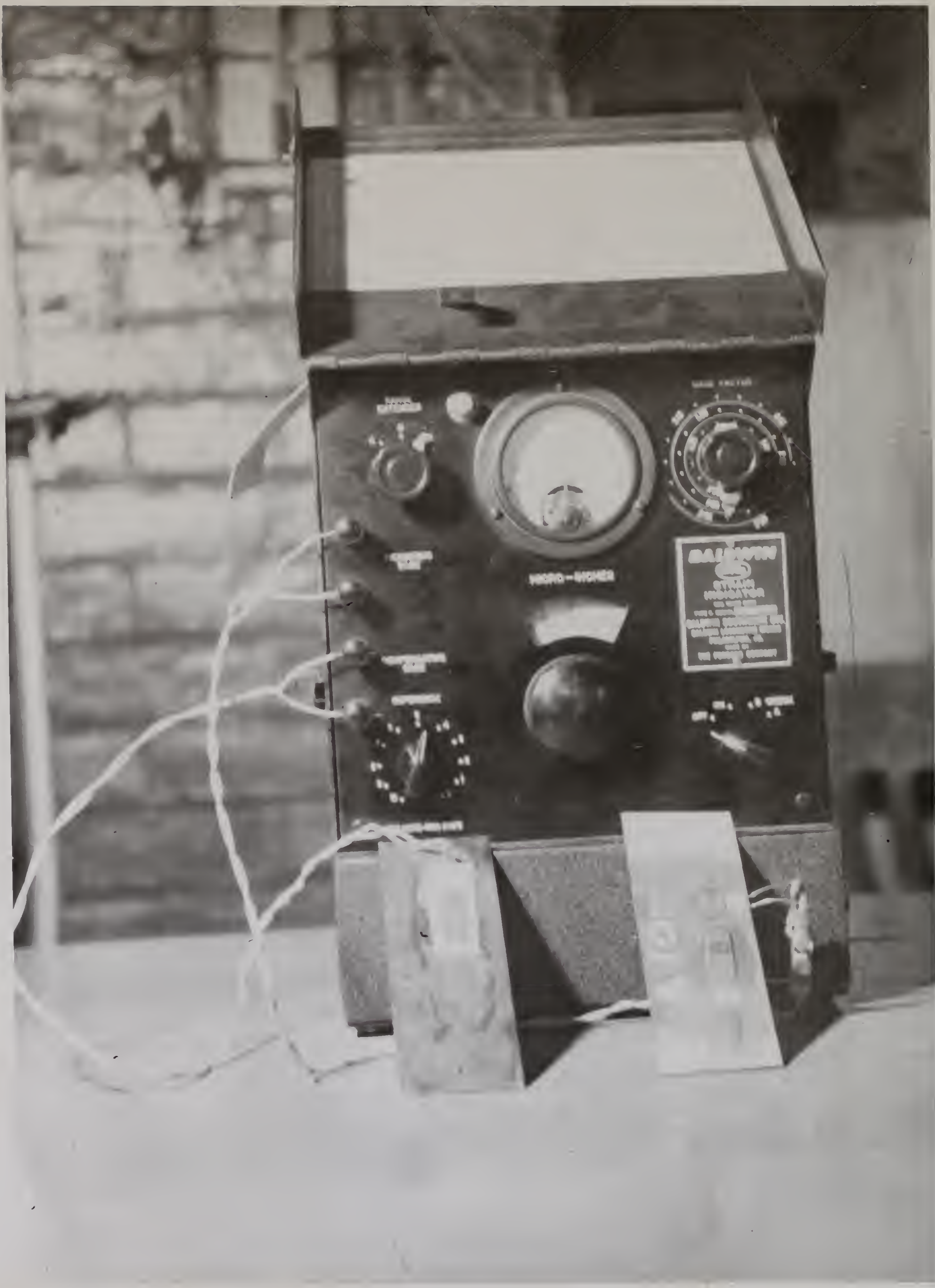
Photograph 1.

Photograph 2.



Photograph 3.



Photograph 4.

Thesis 7477
A2 Acuff
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