FAILURE OF THE LEAD SHEATHING OF ELECTRIC CABLES.

By L. Archbutt, F.I.C.

It has been the practice for many years to sheath electric cables with lead as a waterproof covering, to maintain the insulation. In August, 1908, I received from Mr. J. Sayers, Telegraph Superintendent of the Midland Railway, several short lengths of lead-covered cable removed from wood boxing carried on posts by the side of the line near to Blea Moor Tunnel. This cable was laid in 1896 and had developed defects. The lead covering was not corroded, but was cracked in several places, and my opinion was asked as to the cause. Analysis showed the lead to be almost chemically pure. A determination of the lead as sulphide gave 99·94 per cent., and the only impurities found were:—

	Per cent.
Oxygen	·004
Antimony	·004
Bismuth	·008
Iron	·003
Zinc	·002
Silver	trace

The brittleness was found to be due to a want of cohesion between the crystalline grains, and not to any brittleness of the lead itself. Fine cracks were visible on the inside of the sheath when opened out, and fresh cracks appeared when the metal was bent. These cracks ran between the grains, which were not unusually large. I concluded at the time that the defect was probably due to some impurity, such as lead oxide, which had become trapped between the grains and prevented their perfect adhesion, although the quantity must have been exceedingly minute. Lead, very rich in silver, which has been remelted a great many times to remove the silver, is said to be liable to prove defective when made into sheets, and I thought something of the kind might have caused the defects in the lead from which this sheath was made.

In November, 1910, I received from Mr. Sayers a piece of lead sheath from a 7/15 conductor (power) cable, which was the only lead sheathing which in his experience had not shown signs of deterioration by cracking or corrosion after being in use for several years. This cable had been in use for six or seven years, most of it in iron pipes underground, some passing into brick chambers where portions were alternately wet and dry. A careful analysis of this lead showed it to be of remarkable purity, no single impurity being found in weighable quantity.

In 1912, a piece of lead-covered cable was sent to me which had been laid in soil about 40 years previously, and when dug up was found to be as good as when laid in. I found the lead to be by no means chemically pure, the analysis showing:—

Lead	99·88
Arsenic	trace
Antimony	·014
Tin	·008
Copper	·029
Bismuth	trace
Iron	·006
Zinc	trace
Nickel	nil
Silver	·008
	99·945

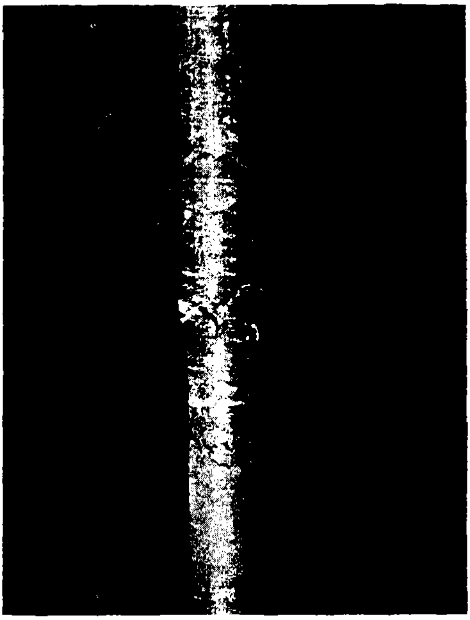

FIG. 1.

The soil in which this cable was laid was a porous, sandy loam, free from carbonates. It contained very little organic matter and very little soluble matter. The aqueous extract was quite neutral to litmus.

In March, 1918, I received from Mr. Sayers specimens from a number of cables used in connection with automatic signalling between Keighley and Steeton. These cables were mostly laid in wooden boxing, supported on wooden posts about 2 feet above the ground and about 8 feet distant from the rails, and had been in use about 10 years. During the previous January, fractures had appeared in the sheathing of these cables, leading to a breakdown of the insulation, and on examining the cables a large number of smaller cracks or incipient cracks were detected. The cables, which were laid together in the boxing, were of different sizes, the thickness of lead ranging from 0·1 inch to 0·04 inch. All the cables were affected, the largest least and the smallest most, the lead covering of the smallest cable being reported to be fractured every few yards. The section between Keighley and Steeton is 2½ miles long, and the cracks extended over a considerable part of this distance. A photograph of a typical defect in one of the cables is shown in Fig 1. On opening out the lead sheathing of this cable, the metal showed a network of fine cracks on the inside, some of which had penetrated through the metal, shown in the photograph, Fig. 2, under a magnification of nine diameters. There were no signs of corrosion. An analysis of the lead gave the following results:—

FIG. 2.
(Originally magnified 9 diameters and reduced by one-quarter.)

Lead	99·928
Arsenic	trace
Antimony	·007
Tin	trace
Copper	·020
Bismuth	·016
Iron	·003
Zinc	·004
Nickel	trace
	99·978

The cracks, as in the case first-mentioned, appeared to be intercrystalline, and, as this type of failure seemed to be common, it was thought desirable that an inspection should be made of the method of sheathing these cables. In modern practice, the sheath is put on to the cable by passing it through the core of a hydraulic press, from which the lead is extruded as a tube enclosing the insulated wires. At the particular works which I visited with Mr. Sayers, Krupp presses are used, and the temperature of the lead is controlled by thermo-couple pyrometers fixed in holes drilled in the press. The temperature of the molten lead used for charging the press, controlled by a thermometer, was said to be maintained at about 740° F. The thermo-couples in the press at the time of our visit indicated

300°-340° F. while the lead was being extruded, but these couples were not less than 10 inches distant from the centre of the die. 400° F. is probably more nearly the temperature at which the lead is extruded. We were informed that in covering a long length of cable the pressure was released before the whole of the lead in the press had been extruded. Molten lead was then run in behind this, and when this had solidified the pressure was put on again. The pressure during extrusion was 20-25 cwts. per square inch. The lead from the melting pot was run into the press through a funnel at each end, and it seemed possible that some oxidation of the lead might occur during this operation.

The defective cables were subsequently inspected *in situ.* They included one large 17-wire, screened, paper insulated cable, with lead sheathing 0·1 inch thick, which had developed only two defects, said to be explainable, two 7 pair, paper insulated cables, Nos. 2 and 3, each 0·59 inch diameter, and an oil-filled power cable. The lead covering on each of the three latter cables was 0·08 inch thick and had developed the following defects in a distance of $1\frac{1}{2}$ miles, *viz.*: No. 2 cable, 25 defects; No. 3 cable, 29 defects; Power cable, 12 defects. A twin, rubber insulated cable, quite small, 0·356 inch diameter, covered with lead 0·04 inch thick, had cracked through and pulled apart in very numerous places. All these cables lay in wooden boxing which was quite dry and clean inside, partly on a gentle incline and partly in a shallow cutting. The defects were found in both positions. A length of No. 3 cable was subsequently cut out for detailed examination from a position where about one half appeared to be sound and the other half badly defective. The makers of the cables, after searching their records, stated that the two 7-pair cables were sheathed with lead in the Krupp press above mentioned, but that at the time they were made temperatures were controlled by mercurial thermometers and not by thermo-couples. The twin cable was sheathed in another press of older pattern. The length of cable actually cut out for detailed examination measured 500 yards between the junction boxes. These are of cast iron, and the cable is sweated into them. I was informed that in unwinding the cable from the drum when laying, the underside as it lay in the boxing would be that under compression on the drum, and so far as could be seen the cracks appeared to be on this side of the cable. It was also stated that the boxing at Keighley had sunk, causing tension in the cable, and there was noticed to be more tension than usual on the cable when cut out. The boxing at this point would, it was said, be subject to more vibration than usual from passing trains. When unwinding the piece of defective cable from the drum on which it was sent to me, the distances were measured between the defective places and found to be as follows:—

	ft.	ins.	
Distance to 1st fault,	217	6	
	3	0	Length of 1st fault.
,, ,, 2nd ,,	103	3	
	2	7	,, ,, 2nd ,,
,, ,, 3rd ,,	56	6	
	2	6	,, ,, 3rd ,,
,, ,, 4th ,,	51	0	
	2	4	,, ,, 4th ,,
,, ,, 5th ,,	55	0	
	1	2	,, ,, 5th ,,
,, ,, 6th ,,	119	3	
	1	3	,, ,, 6th ,,
,, ,, 7th ,,	109	7	
	3	7	,, ,, 7th ,,
,, ,, 8th ,,	78	5	
	4	0	,, ,, 8th ,,

The remainder of the length of cable was sound, except one faulty place at the end. It will be observed that the distances between the faulty places measured, approximately, 50 feet or multiples of that length. The length of cable of this size which is passed through the press before recharging with more lead would be about 200 yards.

Pieces of lead were cut from a part of the cable where there was no visible defect, also from a badly disintegrated part, and analyses of these gave the following results:—

	Sound Part.	Defective Part.
Lead	99·917	99·902
Antimony	·014	·013
Bismuth	·018	·019
Copper	·002	·001
Iron	·0002	·0002
Zinc	·002	·002
Silver	·003	·003
Oxygen	·004	·011
	99·9602	99·9512
Nickel	nil.	
Arsenic and Tin	mere traces.	

Further estimations were made of the oxygen in pieces cut from different parts of the sheathing and also from a piece of new plumber's lead pipe. The oxygen was estimated by the loss of weight on melting the metal in hydrogen and also by weighing the water formed. The results obtained were:—

	Oxygen, Per Cent.	
	By Loss of Weight.	By Water Formed.
Lead from extreme end of cable, apparently free from defects	·004	·004
Lead from piece showing incipient cracks	·005	·005
Lead from part where cracks were well developed	·011	·010
New lead pipe	·004	·004

The amount of oxide found in this lead sheath, where not defective, was the same as in the new lead pipe, and the higher percentages found in the defective part did not seem to be more than might be accounted for by surface oxidation which had occurred since the cracks developed.

Determinations of specific gravity gave the following results:—

	Specific Gravity at 60° F.
Lead from sound part	11·355
Lead from badly cracked part	11·356
New lead pipe	11·352

Freezing-point determinations by the thermo-couple method showed no difference between the sound and defective portions of the lead.

All the above-mentioned determinations having been made with special care and having thrown no light on the cause of the failure, attention was again directed to the micro-structure, and it was found that in all the defective places examined, not only were the cracks intercrystalline, but the shape and size of the crystals were remarkably different in the defective places and in the sound part of the sheath. These differences are shown in the micrographs, after etching with nitric acid, under a magnification of 15 diameters. Figs. 3 and 4 show the crystalline structure of the undamaged part of the sheathing, far away from the faulty part. Figs. 5 to 9 show the structure of the defective part. It will be noticed that in the defective part the crystals are, as a rule, much larger and have straighter and smoother boundaries than in the undamaged part. The cracks follow the course of these boundaries, the crystals being arranged so that the intercrystalline joints run more or less in straight lines.

Being puzzled how to account for these fractures I mentioned the matter to Dr. Rosenhain, and he suggested that they could be explained on his theory that an intercrystalline cement exists in metals which can be caused to flow under stress, leading to a gradual separation of the crystals from one another. The theory is explained in detail in the paper read before the Royal Society by Dr. Rosenhain and S. L. Archbutt[1] in which reference is made to this particular cable failure after the authors had examined a piece of the lead sheathing which I sent to them. Arising out of this suggestion, I have made a number of experiments, and have also examined several other fractured cables.

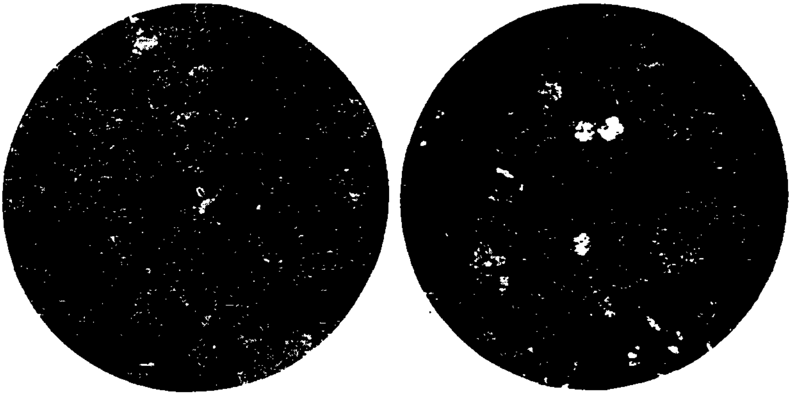

FIG. 3. FIG. 4.

(Originally magnified 15 diameters and reduced by one-quarter.)

The experiments have consisted in suspending pieces of sound lead sheathing from the Keighley-Steeton No. 3 cable in a vertical position, with a weight attached to the lower end of each piece, and observing the effect. Preliminary tests showed that when pieces of the sheathing were pulled in a tensile testing machine, elongation commenced in the case of three different pieces under loads of 109 lbs., 116 lbs. and 126 lbs., respectively. The breaking loads ranged from 260 lbs. to 296 lbs. and the elongation at fracture, measured on a length of 6 inches, amounted to from 45 per cent. to 53 per cent.

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[1] "On the Intercrystalline Fracture of Metals under Prolonged Application of Stress," *Proc. Royal Soc.*, A, Vol. XCVI., 1919.

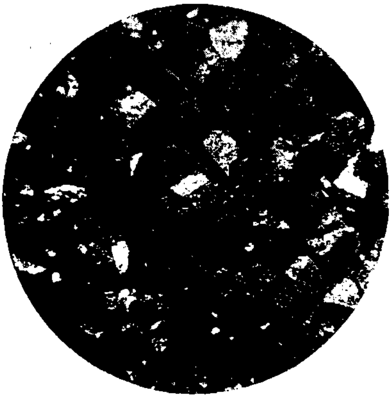

Fig. 5.

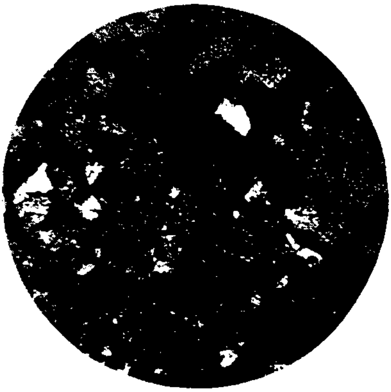

Fig. 6.

Fig. 7.

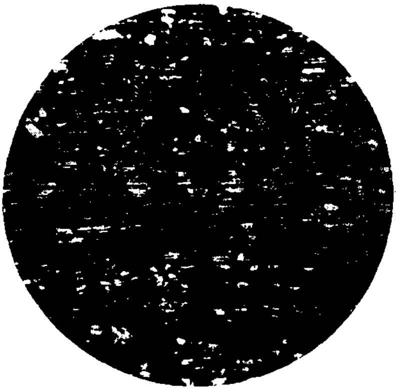

Fig. 8.

Fig. 9.

(All originally magnified 15 diameters and reduced by one-quarter.)

One of the first suspended test pieces was weighted with 112 lbs. After one week it had elongated about 8 per cent. on a length of 30 inches and had developed surface markings showing the crystalline grain contours of the metal. Microscopical examination showed evidence of incipient intercrystalline fracture. A second, shorter test piece, weighted with 100 lbs., was kept under careful observation and the elongation measured at intervals on a length of 6 inches. In 14 days, surface markings had developed, and after 39 days the specimen fractured near to one end, after elongating 23 per cent. between the test marks. The fractured end was cut off, opened out and etched. The crystals seemed to be all quite small and their boundaries irregular. Nothing could be made out by examination of the fractured edges. Incipient cracks which had developed near the fracture are shown in Fig 10. A crack in a third piece, which broke after three months under a load of 84 lbs., is shown in Fig. 11. Both specimens etched with nitric acid and magnified 15 diameters.

FIG. 10.

FIG. 11.

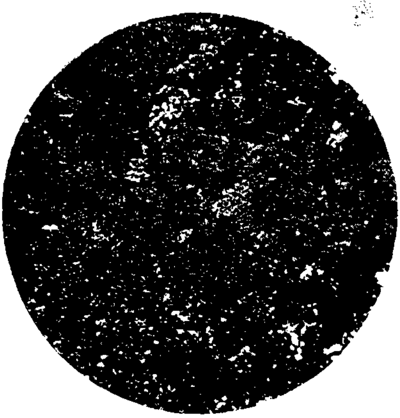

FIG. 12.

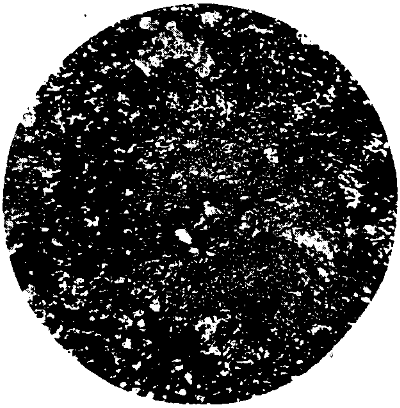

FIG. 13.

(Originally magnified 15 diameters and reduced by one-quarter.)

To ascertain the effect of vibration, to which the fractures in these cables are generally attributed, two test pieces were suspended, each with a weight of 70 lbs. Each of these pieces of sheathing was annealed for 7 days at 250° C. previous to the test. One was placed at one end of a room where there was no perceptible vibration and the other between two file-testing machines in the same room, working day and night and causing a visible tremor in the test piece. The piece under vibration began to develop surface markings in 65 days and broke in about 308 days, after elongating only 15 per cent. The other piece showed some indications of surface markings in 155 days, but not very distinct until after 365 days. It had not broken through, but had begun to crack and show marked evidence of disintegration at the end of 484 days, when the experiment was discontinued. The elongation amounted to only 8 per cent. Figs. 12 and 13 are micrographs from the etched inner surface of the piece broken under vibration, which showed evidence of general disintegration throughout the whole length between the test marks. Careful examination showed the fractures in this specimen to be partly inter-crystalline and partly not. Fig. 14 is a photograph showing the crack and surface markings which developed in the test piece not under vibration.

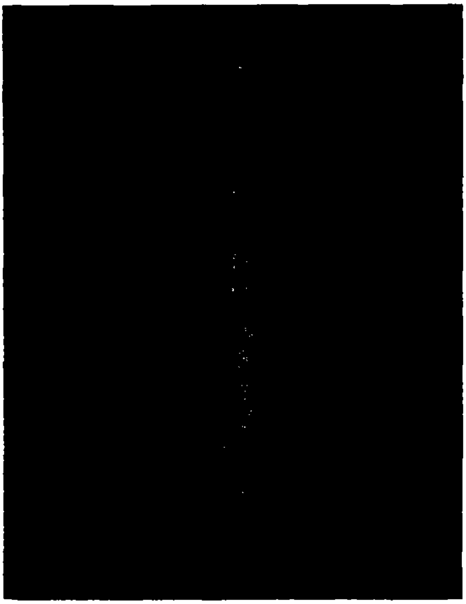

FIG. 14.

To confirm the effect of vibration further tests are being made, but are not yet completed.[1] The test pieces are in duplicate, and the tests were started on September 11, 1920. The two pieces under vibration have again begun to show surface markings before the others, and are stretching more rapidly. In 179 days the pieces under vibration have stretched from 6 inches to 7·10 inches and 7·19 inches, respectively; the two pieces not under vibration have stretched to 6·90 inches and 6·95 inches. Vibration, therefore, has a very perceptible effect in accelerating the rate at which the lead elongates and eventually breaks under stress, but it is not the primary cause of fracture, which is due to stresses in the metal, assisted in some cases by a weak type of crystalline structure. This peculiar structure is not found in all cases of fracture, but I have generally found it where the fractures have been markedly inter-crystalline.

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[1] See p. 34 for final results of these tests.

Lead-covered cable supported on brackets some feet apart is liable to crack, generally near a bracket. A specimen of lead showing a fracture of this kind was sent to me in 1919 by Mr. McMahon, Power Superintendent of the London Electric Railways. It had a single crack about $\frac{3}{4}$ inch long and another smaller crack, both open cracks, but no network of cracks. Microscopical examination failed to show any evidence of inter-crystalline failure, and the cracks appeared to have been caused by excessive stress at the point of support.

Another specimen, sent in 1919 by Lieut.-Colonel Leigh, Chief Electrical Engineer of the L. & N.W. Railway, was from one of two 10-pair, dry core cables, laid in separate grooves one above another in wooden boxing in 1903 in a shallow cutting at Leyland, the boxing being supported on posts distant about 12 feet horizontally and 8 feet vertically from the nearest rail. The posts were fixed in a bank supported by a retaining wall. The lengths of cable affected were perfectly straight and had no bends. The defects occurred chiefly in the upper of the two cables, at irregular intervals throughout the length, and consisted of a network of cracks as in the two Midland Railway cables, but the evidence of inter-crystalline failure is not so plain. Fig. 15 is a micrograph taken after etching from a part where the cracks were close together, forming a fine network. Fig. 16 shows the structure at a part where the network was much more open.

Figs. 17 and 18 are micrographs taken after etching from the lead sheathing of a telephone cable laid in boxing on the Midland Railway near Heysham Harbour in 1908, which was found to have developed numerous circumferential cracks in 1919. The appearance presented is exactly the same as in the case of the Keighley-Steeton cable, the inter-crystalline character of the defects being plain. In this case the positions of the cracks as the cable lay in the boxing were carefully noted and it was found that some were located at the sides, some at the top and some at the bottom. A careful examination of the outer surface of the lead showed a network of crystalline markings, and the cracks formed more or less of a network corresponding with these markings.

An entirely different type of failure occurred in a cable laid in boxing on the Midland Railway viaduct crossing the river Lune at Lancaster, the boxing being clipped to the parapet of the viaduct. This cable was laid in 1910 and was reported in 1919 to be fractured at intervals throughout the whole length of 240 yards. I made a careful examination of the defects in this cable and found that instead of forming a network the cracks were roughly parallel to one another and rather scattered. No markings were visible on the outer surface of the lead sheath, and the cracks had probably been formed before the markings had time to develop. Figs. 19 and 20 show the micro-structure round some of these cracks. The appearance is quite different from the before-mentioned cases of inter-crystalline failure, and it can be seen that the lead has been torn through the crystals and not broken by the crystals themselves being pulled apart, although some of the cracks are inter-crystalline. There was good evidence that severe stresses existed in the lead of this cable, and there would also be much vibration.

It is evident that the long continued action of a stress in lead, much less than that necessary to cause immediate elongation, will cause the crystals to gradually lose their cohesion and come apart, and this type of failure seems to be connected with a weak type of crystalline structure. I have recently examined several pieces of lead sheathing cut from new cables of different diameters at the point where an annular mark is made by the die

Fig. 15.

Fig. 16.

Fig. 17.

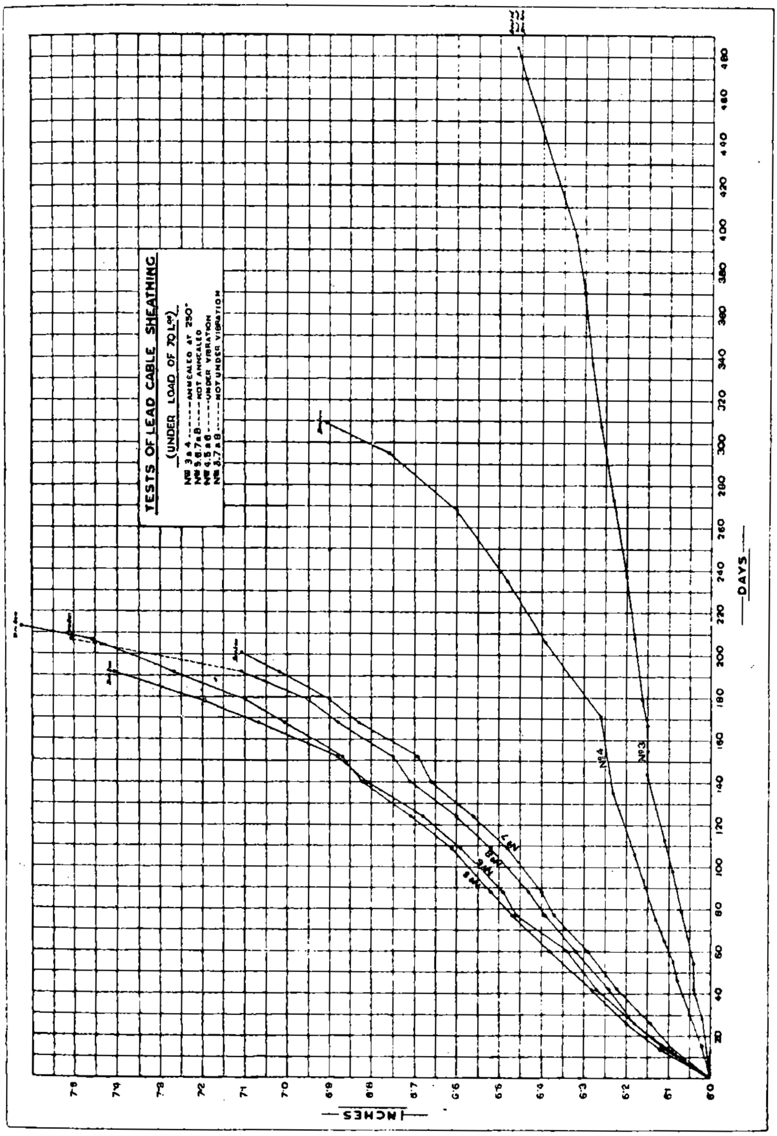
Fig. 18.

Fig. 19.

Fig. 20.

(Originally magnified 15 diameters and reduced by one-quarter.)

when the press is stopped and re-started after being charged with more lead. There is a marked difference in the size of the crystals at this point. In two out of three specimens examined, crystalline growth had taken place in the lead which had passed through the die and had been kept heated by contact with the press, the crystals being much larger on this side of the die mark than on the side which had passed through the die after re-starting the press. In the third specimen the reverse was noticed. I feel no doubt that the peculiar type of structure observed in several of the defective sheaths to which I have referred is developed in the process of



Specimens 4-8 broke under the load, specimen 3 cracked but did not break.

FIG. 21.

extrusion and that the cable makers should investigate to discover the conditions which give rise to it.

Since the above was written, all the remaining test-pieces of the six under a load of 70 lb. have broken, and the curves in the diagram (Fig. 21) show the extension measured between marks 6 inches apart on each piece. No. 8 broke between the test marks, and, consequently, the final extension could not be accurately measured and is shown by dotted line. All the other pieces broke outside the test marks. It will be noticed that Nos. 4, 5, and 6 under vibration stretched more rapidly, and, on the average, elongated more and broke sooner than the corresponding pieces not under vibration. An interesting point to note is that the annealing of this lead made it less plastic under stress. I have had two short pieces supported horizontally between blocks 6 inches apart, with a weight of 5 lb. suspended from a piece of string passing over the centre of each. One piece was annealed for 14 days at 200° C. and one not annealed. After 24 months the piece not annealed has bent 9/32 inch, measured on the length between the blocks, whilst the annealed piece, so far as can be seen, has not bent at all.

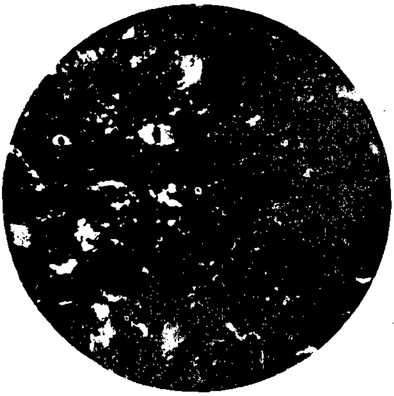


FIG. 22.

(Originally magnified 15 diameters, and reduced by one-quarter.)

Fig. 22 is a micrograph, taken close to the fracture, of the test-piece No. 5 in the diagram. The fracture was to a large extent intercrystalline, and the general appearance bears a considerable resemblance to some of the fractures noticed in the Keighley-Steeton and Heysham cables.

The effect of drastic annealing of the lead seems to have an important bearing on the theory of a viscous intercrystalline cement. One would expect that in the process of annealing the majority of the atoms forming the amorphous material would join up and become part of the crystalline grains, and that not more than a mere film of atomic thickness would remain, which could not possess viscous properties. This would explain why in the bending test the annealed piece of the tube did not show any sign of bending in two years, but in the tensile tests annealing did not prevent the lead from stretching and ultimately breaking with an intercrystalline fracture, and Dr. Rosenhain's remarks in regard to this will be of interest.

I have never been able to understand why an intercrystalline layer should exist of sufficient thickness to be capable of viscous flow, and, if such a film does exist, how it is that metal structures and machine parts under continual stresses do not gradually change their shape or break. In my opinion, no further progress can be made by discussion of this subject, and an effort should be made to study the nature of the intercrystalline matter by means of X-rays, or, if that is not possible, by some new method of attack.

An alloy of lead with 3 per cent of tin had a much finer and very different microstucture from ordinary lead, and appears much less likely to undergo intercrystalline failure. Cables sheathed with this alloy are undergoing trial on the Midland Railway.