# THE STRUCTURAL STABILITY OF LEAD-TIN ALLOYS USED IN ORGAN-PIPES

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In recent years, there has been a growing interest in duplicating the kind of Principal and Flute tone produced by the almost pure lead pipes which were made by Arp Schnitger's predecessors, and often preserved by him when he rebuilt earlier organs. That kind of tone seems to require high lead-content pipes and to be unobtainable from higher tin alloys[1]. As we consider using lead for such pipes ourselves, we view such a venture with some apprehension, fearing that large lead pipes would in a short time collapse because of the softness of the metal. For instance, one rarely finds in early American organs pipes of common metal (20% to 35% tin) made more than four feet long because the builders had learned that longer pipes, indeed, would collapse at the toe or at the mouth. But the question remains for us of how it can be that considerably longer pipes made of even softer material could have remained standing for three or four hundred years without collapsing.

A part of the problem here stems from our intuitive notion of strength. If we compare otherwise identical pieces of metal, one of lead and another of 17% tin, by bending them, it is obvious that the lead sample is not nearly as hard as the other and has less resistance to bending. But this is a more or less instantaneous test, showing us how well the two metals resist very strong forces applied for a short time. What we are really interested in, however, is long-term differences, and it seems that such rapid comparisons do not tell us much about the resistance to forces applied over an extended length of time.

Slow deformation of structural metals is known by metallurgical engineers as 'creep'. Highly refined lead, such as 99.99% corroding lead, is very soft and has poor creep resistance as well. But when traces of other elements such as tin, copper, antimony, and bismuth are added, the resistance to creep improves markedly without causing the lead to become noticeably harder. Of course, the 'pure' lead used by the early builders would not have been highly refined at all, in comparison to today's commercial products. Lead reduced in a blast furnace from Harz Mountains ores, for instance, might have contained 0.06% copper, 0.1% antimony, and traces of bismuth and other elements[2]. There are indications that 1% to 2% tin may have been added as well to pipe metal lead to improve castability[3]. Organbuilders by the time of Schnitger began to add yet more tin to the lead alloy, making it much easier to cast into sheets, and producing a metal much tougher and less susceptible to damage in handling the finished pipes. However, these higher-tin alloys are much more likely to deform by creep.

The *bar graph* shows the effect of adding various amounts of tin to lead (that is, lead with the above-mentioned trace elements). This graph summarizes the results of a comparison test carried out in my workshop at Oberlin College Conservatory. That test in turn was an outgrowth of similar tests suggested by John Brombaugh when I was associated with him as an organ builder some years previously. The test consisted of mounting a number of horizontal bars in a frame, each bar of a different alloy ranging from 1½% to 75% tin, and with all bars made to the same dimensions: 10mm square cross section by 450mm length[4]. All the bars were fixed at one end, and at the other, left free to sag under their own weight. By measuring the amount of movement at the free ends of these bars, I expected in a comparatively short time to gain information suggesting how pipes made of these various materials might stand up over a longer period of time. Some of the measured results are listed in the accompanying table. It is evident that the slowest moving bar is the one made of almost pure lead, while the bar

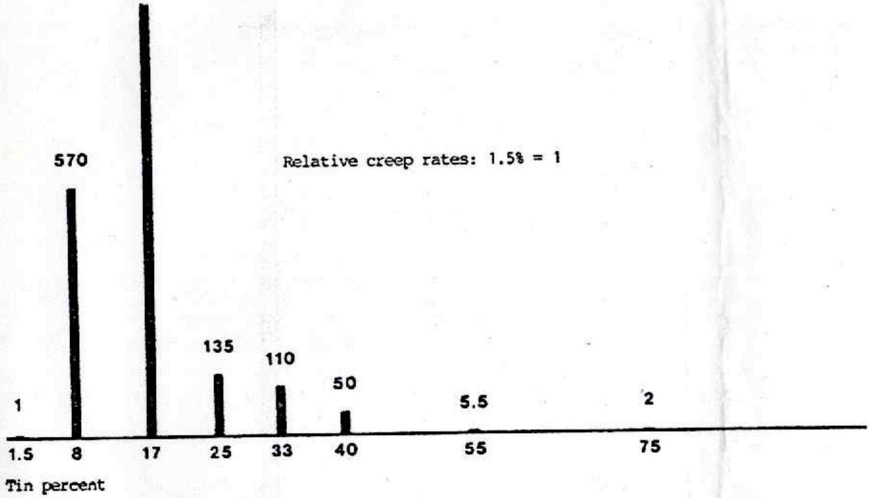

*Table 1*

Comparison of distances moved by cantilever bars of selected tin percentages

| *tin percentage* | *number of elapsed days to reach 150mm mark* | *mm movement in two years* |
|---|---|---|
| 1½ | – days | 7 |
| 8 | 31 | – |
| 17 | 15 | – |
| 25 | 112 | – |
| 33 | 130 | – |
| 40 | 365 | – |
| 55 | – | 42 |
| 75 | – | 13 |

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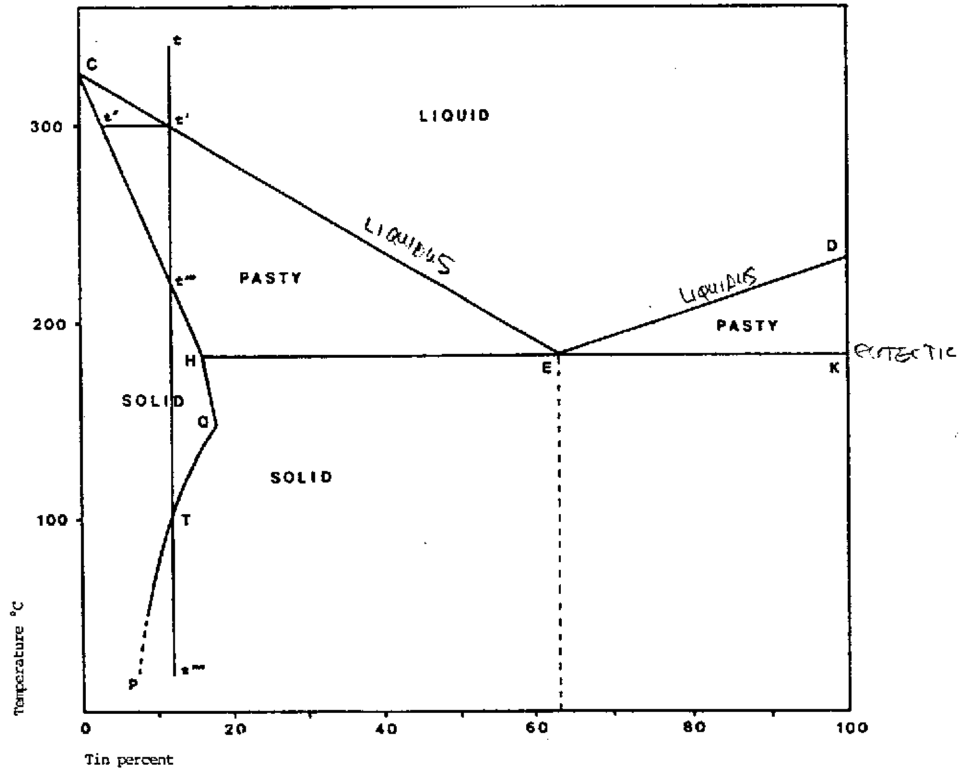
about 60 years, rather than the 15 days of the 17% bar. A comparison of the current rate of movement of the 1½% bar with the observed 7mm per day of the 17% bar as it neared the 150mm mark gives us a creep rate ratio of about 1000 to 1 between the two.



Of course, the numbers gained from this single experiment, involving one kind of mechanical stress situation, should not be taken with any degree of finality[5]. But what is revealing is that the general shape of the graph shows unmistakably that adding up to about 17% tin actually increases the creep rate, and that still more tin again decreases the creep rate.

As background for an explanation of this creep behavior, it would be good to outline how lead and tin interact as mixtures of them pass from the liquid to the soild state[6]. The horizontal scale of the *equilibrium diagram* gives the percentage of tin in the mixture, from pure lead at the left to 100% tin at the right. The vertical scale gives the temperature of the mixture in degrees C. The several lines within the diagram define the boundaries of the possible state of a given composition at a given temperature, whether it is all liquid, all solid, or a slurry of solid particles surrounded by liquid.

It would be reasonable to suppose that a simple straight line connecting the two melting points C and D would describe the melting points for all the various alloys between pure lead and pure tin. However, this is not the case. The lowest melting point of any tin-lead alloy occurs at 62.93% tin, where the melting point is 183° C. This composition, plotted at point E, is called the *Eutectic* composition, due to the particular way it solidifies, and the line H E K represents the Eutectic temperature[7]. The two line segments along C E D, together are called the *Liquidus* line. All compositions of lead and tin at temperatures above the liquidus line are in a completely fluid state. In this state lead and tin will mix with each other in any proportion, without any tendency for either metal to segregate, as oil and water would. Lead and tin are completely miscible in the molten state, and can be thought of as forming a liquid solution. On the other hand, all points below the line C H E K represent metals that are completely solid. The latter line is known as the *Solidus*. Within the two triangles C H E and D K E the state of the metal can be described as a slurry of solid particles surrounded by more or less liquid – more nearly liquid just below the liquidus line, and more nearly solid just above the solidus.

In contrast to the fluid state of the molten metal, where the individual atoms are oriented randomly to each other, the solid state shows a crystalline structure. When pure lead solidifies as the temperature falls below the freezing point, the atoms line themselves up in regularly spaced cubic arrays, with the same interatomic distance in each of three mutually perpendicular directions. These arrays are known as crystal lattices. Within the crystal array of lead atoms it is possible that here and there a tin atom may taken the place of a lead atom. When a liquid solution of tin and lead freezes in this manner, with tin atoms substituting for some lead atoms in the lattice, the result is known as a *Solid Solution*. However, while lead and tin are mutually soluble in any proportion in the liquid state, they are only partially soluble in the solid state. Only 16% tin can be held in solid solution in lead at the eutectic temperature, and generally less than that at lower temperatures. Solidified tin will hardly hold any dissolved lead at all.

The composition containing 12% tin as an example is shown on the diagram by the line t t''''. At point t the mixture is liquid. When the temperature drops to point t' the first tiny crystals begin to solidify, though most of the mass remains liquid. The composition of these first crystals is not 12% tin, but more like 3%, represented by point t'' where the horizontal temperature line t' t'' meets the solidus line C H. Since the proportion of tin removed by the freezing of the first crystals is less than the 12% of the whole mix, the remaining liquid becomes richer in tin and the freezing temperature is lowered slightly. Each succeeding crop of crystals will form with a slightly higher tin content than those preceding, and each layer of atoms coating previously formed crystal grains will also be richer in tin. As the temperature continues to fall, these crystals grow into large grains until finally all the liquid metal is used up and the irregularly shaped grains meet with no liquid separating them. Solidification is complete when the temperature falls to point t''' on the solidus line. Each grain has a single cubic structure internally, but the crystal orientation of any grain will be completely at random to than of its neighbors.

Although atoms in a crystal lattice can move about and exchange places, they can do so only with difficulty. The speed of this process, known as *Diffusion*, is highly temperature dependent. Diffusion, which redistributes the tin atoms in such a way that the solid solution will be in equilibrium, may require years to complete at room temperature, but only hours or even minutes at an elevated temperature[8]. The grains of metal in our example t t''' were formed with relatively tin-poor interiors and tin-rich exteriors. This nonhomogeneous state within each grain is likely to remain so for a very long time, unless the cooling takes place so slowly that the rate of diffusion can keep pace with the rate of cooling.

Suppose that after the alloy has totally solidified, it is maintained at some high temperature between t''' and T, allowing diffusion to bring all the grains to a uniform internal composition. That would bring the alloy to internal equilibrium as long as the elevated temperature is maintained. But a different situation arises when the temperature falls below the point T, crossing the *Solvus* line P Q H. The significance of this line is that solid solutions formed by rapid freezing, cooled to a point below and to the right of the line are in a supersaturated condition. Like a supersaturated solution of salt water, this solid solution is not in equilibrium. Given a sufficient amount of time, the excess tin will be precipitated from the solid solution by diffusion, and the grains themselves may suffer some alteration of structure. In contrast to the rapid precipitation of excess salt from a supersaturated salt water solution, due to its fluid state, precipitation from a solid solution proceeds very slowly at room temperature. Although a solid solution may contain up to 16% tin at the eutectic temperature, and in certain cases up to 18% (point Q on the diagram), at room temperature a solid solution will be saturated if it contains more than perhaps 8% tin, and cannot hold more tin than this while maintaining equilibrium.

It seems hardly a coincidence that the greatest creep rate shown by the graph corresponds to the region of maximum solubility on the equilibrium diagram around points H and Q. The condition under which pipe metal is cast into sheets would certainly be termed as one of rapid freezing. Thus we would expect that a great deal of the metal in a 16% sheet would be structured as a supersaturated solution shortly after being cast. Now if it is true that 8% is the most tin that can be held in solution for the metal to be in equilibrium at room temperature, then eventually half of the tin in solution, or about 8% of the total material in the sheet will have to be expelled from the crystal lattices of solid solution and be dispersed here and there throughout the sheet as tiny pockets of pure tin.

Let us imagine now a large pipe made of this 16% metal which has not yet reached equilibrium. The regions at the sides of the mouth experience the highest level of stress anywhere in the pipe, except possibly at the toe, while at the same time being the weakest structurally[9]. Let us suppose that the weight of the body of the pipe tends to make the metal at the sides of the mouth bend outward ever so slightly. At the same time the hardness or springiness of the metal resists bending beyond this small amount. (This is an example of the short-term strength referred to earlier). Meanwhile, the processes of diffusion and precipitation are going on within the metal, and it is most probable that the migration of tin atoms proceeds in the direction of least mechanical resistance, so that as the excess tin atoms leave the lead crystal lattices, they aggregate at sites in the metal which are tending to be opened up as a result of the applied stress. In arriving at these new sites, they relieve some of the internal tensions within the metal, the metal no longer resists the bending forces so strongly, and therefore those forces are able to bend the metal just a little bit more. So it would seem that there is a continuous cycle of metal being deformed slightly by applied stresses, deformation being resisted by

the metal's hardness or elastic strength, restructuring of the metal because of diffusion and precipitation, bending strains being relieved by the restructuring, further incremental deformation due to the applied stresses, and so on.

The foregoing, it seems to me, is a plausible explanation for the high rate of creep of metals near 16% or 18%. As the tin percentage is increased above 16%, more and more of the metal solidifies as pure tin, and a smaller proportion is composed of the 16% solution. Thus, less of the total amount of the metal is in need of restructuring, and the creep rate decreases accordingly. If there were not such great internal activity taking place due to the lack of equilibrium, the metal could be expected to resist that first slight bending force indefinitely. Since pipe metal of 1½% tin evidently is at or much nearer equilibrium, no great internal restructuring is taking place. If a pipe made of such a metal does not collapse immediately from being subjected to too high a working stress, then it is likely to stay standing without deformation for a long time.

Here now are a few thoughts that may be of help to others investigating the use of lead and common metal alloys for large pipes. The explanation proposed above concerns high creep rates of alloys composed in part of supersaturated solutions. Earlier it was stated that very pure lead also shows a greater creep rate than lead with some trace impurities in it. The presence of small amounts of tin and bismuth in solution may retard creep somewhat by distorting the otherwise flat planes of lead atoms, so that slippage of adjacent planes of atoms under light stresses is retarded. Perhaps an even greater hindrance to slip is obtained by the presence of small amounts of copper and antimony, neither of which enter into solution with lead as a solid. (No more than 0.06% copper can be easily alloyed with lead because even slightly greater amounts require substantially higher temperatures to melt the additional copper into the alloy). Evidently, the small amounts of copper and antimony solidify separately from the lead as hard crystals dispersed throughout the mass in such a way that they retard creep without noticeably affecting ductility. Lead produced for use in the chemical industry already has 0.05% to 0.06% copper alloyed in it. Tin, antimony, and bismuth can easily be alloyed with lead in the organbuilder's pipe shop. Hardening lead by increasing the antimony content may not have the same musical effect as hardening through increased tin content. However, since antimony does not enter into solid solution with lead, the problem of unstable, supersaturated solutions does not arise, so that antimony may have a advantage over tin in some cases. One such instance might be to render lead languids less susceptible to damage during voicing[10]. Some caution must be exercised since there is some evidence that antimony in excess of 1% may cause cracks to appear in the cast metal sheets, due to its brittleness.

It is important to pay attention to the metal thickness used for large pipes. The metal should be much thicker at the mouth end of the pipe, where extra strength is needed, and thinner for the rest of the body, in order to reduce the weight bearing on the lower end. The softness of lead makes it relatively easy to shape the feet of large pipes out of plates 5 or 6mm thick, which is sufficient for pipes 12 to 16 feet long and does not require the use of additional copper stiffening inserts.

More needs to be learned about how to lessen the risk involved in using alloys such as 17% tin. We already know that pipe metal in earlier times was hammered, although the work-hardening from this is not permanent since lead will anneal at room temperature. One effect of hammering may be that by

Some form of heat treatment is likely to be the most effective way of stabilizing such metals. There are reports of old pipes being boiled in water after fabrication, and one wonders whether this may have been done to render the metal more stable[12]. Based on the discussion of supersaturated solid solutions, the logical method of stabilizing the metal would seem to be to reheat it in an oven to some point above the solvus curve P Q. At such a temperature the solution should easily be brought to equilibrium for that temperature. Presumably, if the metal can then be cooled slowly enough, internal restructuring can take place readily because of the elevated temperature, and the amount of tin in solid solution will gradually decrease as the temperature decreases, arriving finally at room temperature with the excess tin no longer in solution. Whether the rate of cooling necessary to bring this about is reasonable from the standpoint of the overall time required is a matter for additional investigation.

These observations have been offered in order to further our understanding of the creep behavior of certain lead-tin alloys, and in the hope that the future will see a greater advantage being taken of the special musical properties of high lead alloy pipes, with confidence in their long-term structural stability.

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*Notes*

1 Charles Fisk refers to lead as having astonishing agility of speech, of having a softness about it and yet great carrying power, while the sound of tin he characterizes as one of refinement, lending itself to producing rich *pleasing* overtones, 'Some Thoughts on Pipe Metal', *Music* XII (1978) No. 11, pp21-22

2 *Zeitschrift für das Berg-, Hutten-, u. Salinenwesen im preuss. Staate,* XVIII (1870), 205

3 Based on information in the possession of John Brombaugh. Difficulties with casting high-lead sheets are aggravated as the tin content falls below about 1½%

4 Lead bars 15% to 20% longer than this could not sustain their own weight. At this 450mm length, the stresses are just below the ultimate strength for lead

5 For example, the 25% bar does not seem to have moved as much as would be indicated from the trend of the other bars. Other testing is needed to gain any real quantitative comparisons

6 This description is largely based on relevant portions of the work by G.H. Gulliver, *Metallic Alloys: Their Structure and Constitution,* fourth ed. (London, 1921). The equilibrium diagram (p110) appears to be based on more detailed data than others appearing elsewhere in regard to the position of the solvus line

7 The eutectic structure at 63% tin consists of very thin layers of lead-tin solution alternating with layers of pure tin, at a fineness of perhaps 4000 to 6000 layers per cm. The appearance of spotted metal is due to the fact that the material at the boundaries of the spots is near the eutectic composition

8 Theodore Allen, Jr., and John K. Anthony, 'Phase Diagrams and the Simple Alloy Systems', *Engineering Metallurgy,* (N.Y., 1957), pp99-100

9 Werner Kluge, 'Die statische Festigkeit von Orgelpfeifen', *Acta Organologica,* XIV (1980), pp251-262

10 It is worth noting here that while Dom Bedos speaks of tin and common metal for pipe bodies and feet, he says that languids should be made of *pur plomb.* Perhaps he was aware of the fact that thin languids of common metal would too easily deform with the passage of time, and thus upset the speech of the pipes. *L'art du facteur d'orgues,* Paris (1766), p343

11 Philip C. Rosenthal, 'Factors Affecting Engineering Properties', *Engineering Metallurgy,* (N.Y., 1957), pp45-46

12 Article by Bernhardt H. Edskes on the Nieuw Scheemda organ restoration, in *Arp Schnitger en zijn werk in het Groningerland,* (Groningen, 1969), p32