Characterisation of lead pipes used in the water industry: extrusion processing, alloy microstructure and their role in service failures

N. Starling*[1,2], H. M. S. Belmonte[1], M. A. Shepherd[1], M. J. Mulheron[2] and P. A. Smith[2]

The issue of leakage within the water distribution system is one of importance not only at an economic level for the industry, but also as a result of an environmental agenda addressing issues of water sustainability. The present work is concerned with leakage from lead based assets, in particular distribution pipes. Very little is known about the failure mechanisms within lead based assets. The present paper presents the findings from a study in which lead samples from intact and failed pipes, sourced from the Thames Water area, have been examined. The failure mechanisms have been identified at the macroscopic level and the pipe microstructure has been characterised – aspects of the microstructure control particular properties of the pipe (e.g. strength, creep and fatigue behaviour) and so may contribute to the potential failure modes. The present study is the first stage in a programme of work designed to develop a better understanding of the failure modes in lead assets, leading to the formulation of a more effective condition assessment model.

Keywords: Lead, Condition assessment, Microstructure, Mechanical properties

Introduction

The issue of water leakage within the water distribution network is one of importance to water companies not only at an economic level, in terms of a lost resource and more recently because of financial penalties that may be imposed by the regulatory bodies for non-compliance, but also because of a wider environmental agenda including issues such as water sustainability. It has also become increasingly more important that water companies are seen by customers to be setting a good example by fixing leaks as soon as possible, especially in times of drought.

It has been estimated by Ofwat that >30% of the total leakage from the water distribution system in the UK is associated with service pipes.[1] A service pipe runs from the water main to a user, via an outside stop valve (OSV), and comprises a supply pipe and a communication pipe (Fig. 1). The communication pipe runs from the water main to the OSV, located near the boundary of the user, and the supply pipe runs from the OSV into the property.

Communication pipes, which are the responsibility of the water company, have been manufactured from a number of materials including lead, iron and more recently plastics. Although new lead pipes have not been installed since the early 1970s, it is estimated that there are ~1·4 million lead communication pipes still in operation within the Thames Water Network alone.[2] This accounts for ~60% of the total number of communication pipes within the Thames Water Network; the total associated length of lead pipe is ~8000 km.

These lead pipes are known to fracture in service. However the causes of these failures do not appear to be well understood and consequently there is no 'off the shelf' method of condition assessment for lead based assets, of the sort that was developed for cast iron pipes in the early 1980s. Lead alloys are complex materials with mechanical properties that depend strongly on composition and microstructure; moreover, they are susceptible to damage under service conditions involving creep and fatigue loading (in pipes perhaps arising from ground loading and thermal effects) and corrosion. There is also a distinct lack of contemporary research into the behaviour of lead alloys, with much of the work confined to the early half of the twentieth century.

Work in the field indicates that a significant number of repairs are carried out on leaking lead service pipes, but the mechanisms that cause these failures are not fully understood. Certain types of failure may also be more detrimental than others and their different contributions to leakage are unknown. Pipes are replaced either as part of the water main renewal

[1]Thames Water Utilities Ltd, Research and Development, Spencer House, Manor Farm Road, Reading RG2 0JN, UK
[2]School of Engineering, University of Surrey, Guildford, Surrey GU2 7XH, UK

*Corresponding author, email neil.starling@thameswater.co.uk

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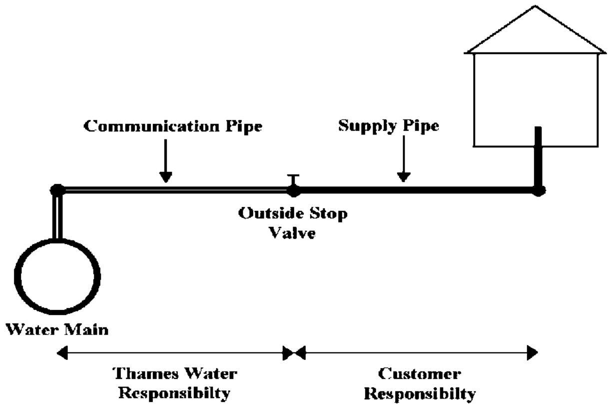


1 Schematic of service pipe, showing communication and supply elements

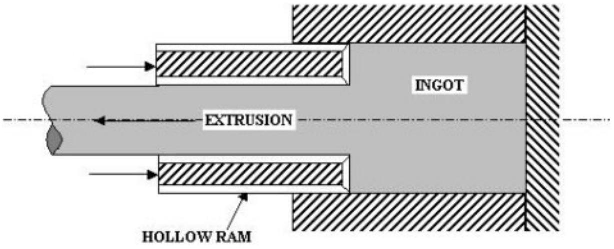
programmes or as leakage is detected. The present work is part of a study designed to develop a better understanding of the failure of lead pipes in service and so to develop a condition assessment tool that could facilitate a more targeted replacement strategy.

The structure of the present paper is as follows. We begin by reviewing, briefly, the manufacturing methods used for the production of lead pipes as these have a role in the development of the microstructure and the introduction of defects, which is relevant in understanding failure mechanisms. The set of lead pipes available for the current work is then presented. These were sourced from the ground, where some had experienced failure in service. The failure mechanisms are summarised. The preparation of metallographic sections from these pipes sourced from the ground is then described, followed by microstructural observations, which are linked to the available literature. This enables factors contributing to the pipe failures to be identified and conclusions to be drawn.

Manufacturing methods

Lead pipes were manufactured by a process of extrusion as covered by the British Standards, BS602 (1935) and BS1085 (1943), which were subsequently amalgamated to form BS602:1085 (1956) – 'Specifications for lead and lead alloy pipes for other than chemical purposes'. During an extrusion operation, lead is formed into a continuous length of uniform pipe by forcing the lead to flow under high pressure and temperature through a die aperture. The process was commonly carried out in a vertical hydraulic press, using a method of inverted extrusion. In inverted extrusion the normal practice is that the die is attached to the head of the press frame and the charge container moves over the die, pushing the charge though it, as shown in Fig. 2. After the 1950s, a method of horizontal continuous extrusion began to be used more widely.

For the extrusion process shown in Fig. 2, it is necessary to replace the charge after each successive motion of the charge container. In the case of continuous extrusion, however, the lead is forced through the die by means of an extrusion screw in one continuous operation, thus avoiding the difficulties encountered with intermittent charging. As will be discussed later in the present paper, whether the pipe is manufactured by a method of vertical hydraulic extrusion or continuous extrusion will affect the grain



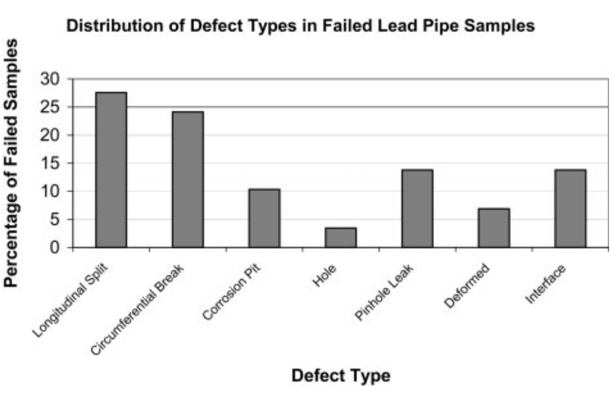
2 Schematic illustration of inverted extrusion process

size and shape along with introducing other microstructural characteristics/defects into the pipe.

Pipes examined in present work

In total more than 60 lead pipes were sourced from the Thames Water region. The pipes are typically ~23 mm outside diameter with a bore of ~12·5 mm. The samples were obtained through the Customer Side Leakage teams and thus were targeted as contributing to leakage in one form or another. The sample set comprised both intact lead pipes and pipes which had failed in service, although it was not possible in all cases to obtain that section of the pipe that contained the failure.

Of those pipes obtained which had a failure (as apparent from visual inspection or from pressurisation of the extracted pipe section), different failure types can be classified. The WRc plc employs a classification system that enables failed pipes to be assigned to one of seven categories.[3] This classification system has been applied to the failed lead pipes in the present work in Fig. 3. Of these failure modes, the longitudinal split and circumferential break are self-explanatory. Some differentiation needs to be made between a corrosion pit and a hole. A corrosion pit will be present on pipe that exhibits visible signs of corrosion whereas a hole may be present on an otherwise sound pipe and may possibly indicate mechanical damage. A pinhole leak is such that it may not be visible until a low pressure test is carried out. A 'deformation' failure is, as the name suggests, where the pipe has been crushed or deformed, either as a result of its installation or possibly owing to ground loading. An 'interface' failure is where a leak is apparent at the interface between the pipe and another asset such as polyethylene pipe or OSV. Any one pipe may contain a number of different failures. It can be seen from the graph that the most frequently occurring failures are longitudinal and transverse (or circumferential) fractures.



3 Distribution of defect types in failed lead pipe samples

In order to understand the origins of the longitudinal and transverse fractures in more detail, microscopic examination of the pipes was undertaken, as described in the two sections that follow.

Sample preparation for metallographic examination

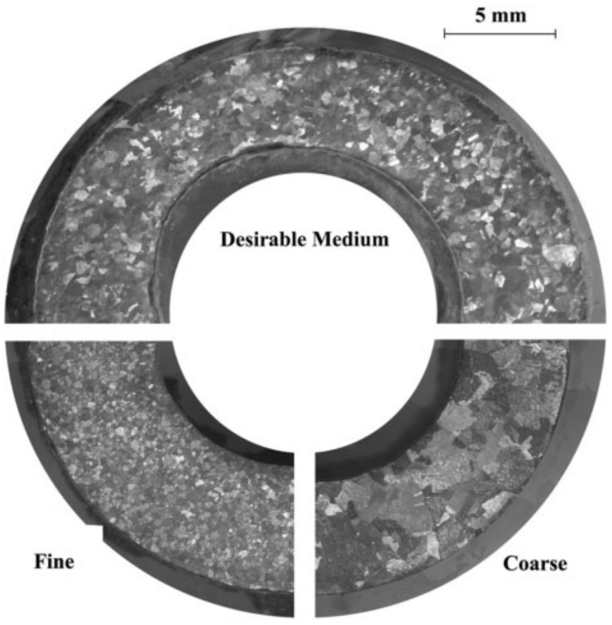
Lead has a relatively low recrystallisation temperature, compared with other metals. This means that it is vital that any unnecessary deformation, excessive friction or heating is avoided in the metallographic preparation of lead. If extensive recrystallisation occurs during sample preparation then this may lead to the formation of a surface microstructure that is not representative of the underlying microstructure of the lead under examination. This is one factor which makes the preparation of lead for metallographic examination inherently difficult. A number of preparation methods have been cited within the literature.[4–7]

The first and most important step in preparation of the lead metallographic sample is sectioning the sample from the parent supply pipe. This must be achieved with as little deformation and heating of the lead as possible. Slepian and Blann[4] and Hofmann[5] describe a method whereby a fine hacksaw or fret saw is employed, with a new blade used for each sample. This avoids additional material becoming embedded in the lead with each successive sample. This method provided the level of accuracy needed with minimal deformation and heat generation within the lead, and was the method adopted in the present work.

Once samples were sectioned, the cut face was ground by hand using 320 grit silicon carbide paper to ensure that it was plane; during this process a constant flow of cold water was run over the sample to minimise heating and to assist in the removal of particulates that may become embedded. The samples were then mounted using Struers Epofix Resin. The cure of this resin is non-exothermic and so no additional heating of the sample occurs.

Once the samples had cured in the mounting resin the next stage was to grind the face to be examined. Slepian and Blann[4] suggest three grinding stages using 320, 400 and 600 grit silicon carbide papers, whereas Ednie[6] suggests using up to 1200 and 4000 grit to minimise the number of embedded particles from the paper and to remove any surface scratches from both the cutting and previous grinding stages. In practice, a combination of these two methods was employed, whereby a grinding method consisting of five stages was utilised, using 320, 500, 1200, 2400 and 4000 grit silicon carbide paper (on a Struers Planapol grinding machine). Both Slepian and Blann[3] and Ednie[5] suggest a grinding force of $\sim$100 N. Trials suggested that this was too high, however, and the force was reduced to 60 N to minimise deformation of the lead. Time limits for each successive grinding stage were not predetermined and each stage was continued until evidence of the previous grinding stage was removed.

Final polishing of the sample was carried out using 3 and 1 μm diamond abrasives followed by a 0·25 μm alumina abrasive. Even after extensive polishing, a number of fine scratches were sometimes still evident on the surface of the lead; these can arise from something as simple as washing the surface of the lead with cotton wool, which serves to highlight its friable nature. Before etching, it was also possible to observe small amounts of surface deformation to the lead and a number of embedded silicon carbide particles entrapped during the grinding operations. In order to remove these imperfections and remove any recrystallised layer produced from the grinding and polishing an aggressive etchant is needed.



4 Variation in grain size observed in lead pipe samples

There are in excess of 25 alternative etchants for lead cited within the literature, and their use depends on the composition of the lead and the required result. ASTM#114 suggests an etchant that consists of three parts acetic acid, four parts nitric acid and 16 parts water. The etchant is applied by immersion of the sample for 25–40 min, or until the grain structure is visible with the naked eye. It was felt that this etchant was sufficient to remove the recrystallised layer on the surface of the lead and produce high grain definition. Once etching was complete the sample was washed with a stream of methanol and air dried.

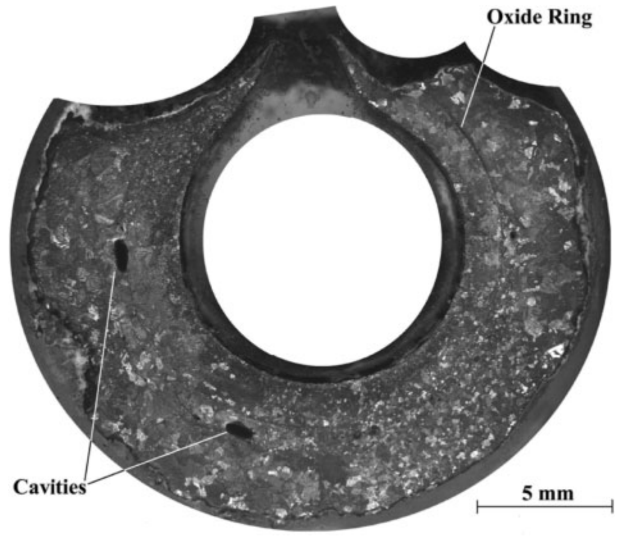
The polished samples were examined using a Zeiss Axiophot light microscope with image capture using a Zeiss Axiocam and Zeiss Axiovision image processing software. As indicated earlier, more than 60 lead pipe samples have been examined during the course of the study. In the next section, representative examples are used to show the range of microstructures encountered. Particular features of interest are the grain size and grain size distribution shown by the samples, together with any characteristic defects. From this, it is possible to comment upon how these may influence the failure modes seen in practice.

Pipe microstructures: observations and discussion

Grain size and size distribution

The grain size was found to vary significantly. Figure 4 shows a number of partial cross-sections from pipes with a range of microstructures; one section exhibits the

5 Lead pipe sample exhibiting 'zoned' grain structure



6 Failed lead pipe showing oxide ring and associated cavities

'desirable medium grain size' ($\sim$0·5 mm) specified by the British Standard, while the others exhibit the extremes of coarse and fine grain sizes that were seen.

It is apparent from the literature that the grain size can influence, significantly, the mechanical properties of lead. With regard to the influence of grain size on the tensile strength of lead, Garre and Muller[7] found that the tensile strength of lead increases with decreasing grain size, as for most metals, owing to the grain boundaries acting as a barrier to plastic deformation.

Turning to the long term properties, the rate of creep in lead varies depending on the grain size. Hanffstengal and Hanemann[8] showed that at low stresses ($\sim$0·5 MPa) and temperatures, fine grained lead (grain size d of 0·2 mm) creeps more quickly than coarse grained lead (d=7 mm). The same trend, of decreasing creep rate (or creep strain after a given time under stress) with increasing grain size was reported by other workers.[9,10] In long term tests at higher stresses ($\sim$2 MPa), however, there was a tendency for recrystallisation and grain growth to occur within the lead, thereby decreasing its resistance to creep.[8]

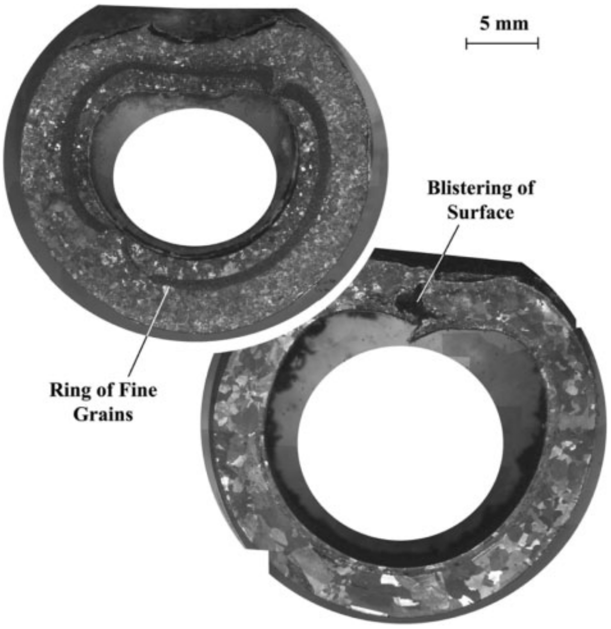
Hopkin and Thwaites[9] also carried out extensive experiments to investigate the effect of grain size on the fatigue strength of lead. They used an alloy with 0·85% antimony, which meant that the lead alloy was not subject to recrystallisation during the tests. The grain size of the lead was controlled by varying the extrusion temperature. From fatigue tests carried out at a frequency of 50 Hz, they showed that as the grain size increased, the fatigue strength decreased, although the effect was fairly small. These tests are consistent with work carried out by Gohn and Ellis[11] who conducted tests to simulate the influence of daily temperature fluctuations on lead cable sheaths by applying stress to the material at a frequency of a single stress cycle each day. They showed that in various lead–tin alloys the fatigue strength increased with decreasing grain size, but again only to small extent.

In order to strike a balance between good creep resistance, good fatigue resistance and tensile strength, the British Standard specifies that under metallographic examination, lead pipes should exhibit a uniform microstructure with a 'desirable medium grain structure'. This equates to a grain size of $\sim$0·5 mm. Many of the samples examined in the present work do not show such a mean grain size. Furthermore, many of the pipe sections exhibited what is cited commonly as a 'zoned' grain structure. This is characterised by circumferentially opposed areas of fine and coarse grains. This zoned structure is a product of bending and coiling of the lead pipes upon leaving the extrusion press, which subsequently results in recrystallisation and grain growth within the pipe.[12,13] A typical zoned structure is shown in Fig. 5. The regions of coarse grains are clearly visible in the upper and lower quadrants of the section; with a visible transition from 'fine' to 'coarse' grains.

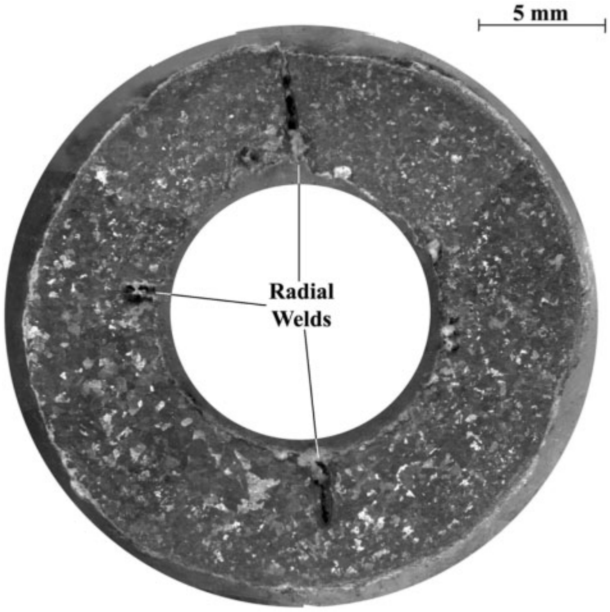
Butler[14] found that in creep tests under internal pressure, those pipes that exhibit a zoned structure showed non-uniform expansion owing to the differing rates of creep between fine and coarse grain lead. He also showed that in fatigue tests there was a tendency for cracks to propagate at the boundary between the coarse grained and fine grained regions. This can be attributed to the presence of stress concentrations at the transition zone. Butler noted that the fatigue strength of a lead pipe with a zoned structure is less than that of a pipe with uniform structure whether it is fine or coarse. In practice quenching the pipe as it leaves the extrusion press can prevent zoning.

Presence and role of defects

Many pipes exhibit defects as a result of the extrusion process. One such defect is when the pipe has a 'scarf' joint running longitudinally. This appears as a ring of oxidised material, when the pipe is cut transversely. This oxide layer is introduced during the extrusion process as the charge is replaced. As the slug from one operation is left in the container, a layer of oxide is formed on the surface. A new charge is then placed in the container on top of the oxide layer and the extrusion process continues. This layer of oxide is then dragged through the length of the pipe as the extrusion process takes place. Figure 6 shows a transverse section from a failed



7 Defects resulting from change in charge in extrusion press



8 Lead pipe sample with longitudinal splits resulting from improper welds at spider arms

lead service pipe and the oxide ring is apparent. There are weak metal/oxide interfaces associated with the oxide layer and associated with the interface is the occurrence of cavities, which result in a local reduction in cross-section. The lead pipe on either side of the oxide rings may show different characteristic grain sizes with associated problems as highlighted earlier.

Other problems can also arise from the process of replacing the charge in the press during the extrusion process. Owing to a number of factors such as friction along the walls of the container and the internal surfaces of the die block, along with higher temperatures at the centre of the charge, movement towards the die block is fastest in the middle. This results in the lead from the new charge protruding in to the lead from the old charge inside the forming chamber. This phenomenon exhibits itself in the microstructure in the form of 'metal tongues'. These metal tongues ultimately meet, to form weld seams at two circumferentially opposed areas of the pipe. This is illustrated in Fig. 7, by the ring of fine grains. In very extreme cases, for example if the ring is very close to the surface of the pipe, this can cause blistering of the surface owing to an insufficient weld between the charges.

It should be noted that oxide layers are not introduced to the same extent when a method of continuous extrusion is utilised, as there is no need to stop the press to replace the charge. Hence the defects described above are not generally seen in continuously extruded pipes.

Another defect that arises as a direct result of the extrusion process is particular to those presses which utilise a bridge die. In such a set-up, the mandrel bar is connected to the die by spider arms, which can range in number from one to four. This can cause problems because the radial welds, which are formed as the lead reunites after the extruded section has passed the spider arms, are often of an imperfect nature. This is exacerbated if oxide and dross contained in the charge are drawn out behind the arms on extrusion, as this will certainly inhibit the formation of a strong weld between the two joining parts. In extreme cases the use of a bridge die may lead to the formation of longitudinal splits from the sites of the joins. A transverse section illustrating poorly formed welds is shown in Fig. 8.

Many of the defects seen in the extrusion process are often ascribed to the extrusion temperature being too low. This prevents the oxide and dross in the melt from rising to the surface of the charge and so promotes the formation of internal defects. It has been noted already that many of the microstructural defects associated with the extrusion process can be avoided by using a method of continuous extrusion. It was also observed by McKeown and Hopkins[14] that the grains in lead pipes extruded on the continuous press were uniform in size and structure, while those produced on the hydraulic press produced a grain structure that was more irregular in size and structure. Therefore it would seem that those pipes produced on a continuous extrusion press would tend to exhibit a more desirable grain structure as well as containing fewer defects.

Conclusions

The issue of controlling leakage within the water distribution network is one of great importance and in order to control one aspect of this leakage, a better understanding of the failure modes in lead service pipes is valuable. As a contribution towards this aim, the microstructure of lead service pipes, the majority sourced from the Thames Water Network, has been examined. It has been shown that the observed microstructures differ significantly from pipe to pipe, exhibiting grain size variation (or zoning) and a number of defects (oxide rings and improperly formed internal welds), directly attributable to the manufacturing process.

The defects identified from the microstructural study certainly play a major role in the occurrence of longitudinal and circumferential failure in service. It has been shown that the microstructural defects of both zoning and radial welds can lead to the formation of longitudinal splits. In the case of zoned microstructure, stress concentrations arise at the interface between fine and coarse grained regions, which may lead to failure. In the case of poor radial welds, the inherent weakness in the weld can lead to the propagation of large longitudinal cracks. The prevalence of such manufacturing defects within the samples may lead to complications in formulating an effective method of condition assessment as accurate records of pipe manufacture and date are not available.

The literature also suggests that the large majority of circumferential failures seen in service can be attributed to fatigue failure.[15–17] This is an aspect that may be investigated further within the present work.

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