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Subsea power cable sheathing: an investigation of lead fatigue performance

Luigi Mario Viespoli[a]*, Audun Johanson[b], Antonio Alvaro[a,c], Bård Nyhus[c], Filippo Berto[a]

[a]Department of Mechanical and Industrial Engineering, Norwegian University of Science and Technology (NTNU), Richard Birkelands vei 2B, 7034, Trondheim, Norway
[b]Nexans Norway, Innspurten 9, 0663 Oslo, Norway
[c]Sintef Industry, Richard Birkelands vei 2B, 7034, Trondheim, Norway

Abstract

The protection of subsea power cables against electrical failure is achieved by the use of a watertight layer. Due to its properties of chemical stability and ductility, lead has been the material of choice for this purpose for several decades. Due to the low melting temperatures of lead alloys, their behaviour is strongly influenced by time-dependent phenomena, such as creep and recrystallization, which become more prominent for lower strain rate deformations. In order to understand the performance of the alloys of interest under cyclic loading experienced during and after installation in combination with the different variables influencing its behaviour, extensive testing is necessary. This manuscript presents the results of fatigue tests at two different strain rates for an alloy of industrial interest. The tests are monitored with the aid of digital image correlation, which greatly reduces the uncertainty on the quantification of the real strain field. The post-mortem fracture surfaces are investigated through scanning electron microscopy and metallurgical characterization to help understanding the differences in the failure modes active in the different stress/strain regimes.

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Keywords: Lead; Fatigue; Creep ; Digital Image Correlation ; Fracture

* Corresponding author. Tel.: +47 459 13 281
E-mail address: luigi.m.viespoli@ntnu.no

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1. Introduction

The presence of a chemically stable and permanently watertight material layer is required to prevent the electrical failure of high voltage subsea power cables. This sheathing layer is often made of lead alloys, due to the ability of these materials to comply with the deformations imposed by the manufacturing process and the easiness of extrusion, important for the production process. Although power cables with lead sheathing are typically not used in dynamic riser systems, the lead sheathing in cables designed for static applications will be nevertheless subjected to various cyclic loads throughout its operational life including temporary dynamic suspension during installation or jointing and thermal deformation of the cable section. The low melting point of these alloys, inferior to 600 K, causesviscous phenomena to occur already at room temperatures. Creep deformation influences the static and fatigue performance of such alloys. The topic of creep and its influence on fatigue has been thoroughly studied in the fields of energy production and microelectronics (see Kassner (2015), Pang et al. (1998), Lall et al. (2016), Motalab et al. (2012), Farghalli et al. (1974), Kassner (2000), Anand (1982), Brown et al. (1989), Dowling and Norman (2013), Wong et al. (2016), Viespoli et al. (2019)), while in the case of lead alloys used for the production of subsea power cables most of the works available in the open literature date back to several decades ago (see Feltham (1956), Sahota and Riddington (2000), Harvard (1972) Dollins and Betzer (1956), Anelli et al. (1988)). Research on this topic has risen to a new actuality due to the will of the industry community of optimizing the designs of subsea powerlines, with the clear spirit of producing a positive impact both on the environment and on production. Within the framework of this renewed interest, the microstructure and tensile behaviour, Viespoli et al. (2019), steady state creep, Viespoli et al. (2019), the influence of local discontinuities on the fatigue resistance (see Viespoli et al. (2019) and Johanson et al. (2018)) and the full-scale fatigue performance, Johanson et al. (2019), were investigated for two lead alloys of industrial interest. The aim of this manuscript is to integrate the aforementioned series of results with the results of fatigue testing at two different nominal strain rates and the fracture investigation focused on qualifying the correlation between the loading conditions and the dominant failure mode.

2. Fatigue testing

The scope of the fatigue testing was to characterize the fatigue performance of the commercial cable sheathing lead “E” alloy. The chemical composition of the alloy can be summarized as follows: 99.3 wt % Pb, 0.45-0.55 wt % Sn, 0.15- 0.25 wt % Sb, where the addition of Sb is made in order to improve the tensile and creep resistance of the alloy predominantly through solid solution hardening. The alloy is however slightly super-saturated and some precipitation hardening is expected. The tensile properties of this alloy are, at room temperature, strongly dependent on the strain rate, Viespoli et al. (2019). In the case of monotonic tensile testing, for the strain rates of interest in this series of fatigue tests (1E-2 and 1E-3 s-1), no important reduction in stress for a given strain level is recorded while a marked drop of tensile strength happens reducing the strain rate to 1E-5 and 1E-7 s-1. This most probably indicates a reduction of the influence of thermally activated dislocation motion for strain rates higher than 1E-4 s-1. The conclusion that creep deformation for the present alloy is dislocation driven for strain rates over 1E-8 s-1 is drawn from the observation of the exponent correlating applied stress and the resulting strain rates, which is in excess of 5 for stresses over 5 MPa, Viespoli et al. (2019). For cyclic testing the behaviour is different, and the stabilized cyclic properties are diverse already passing from 1E-2 to 1E-3 s-1 in strain rate, see figure 3. Considering the Ramberg-Osgood approximation for the stabilized cyclic curve in the form:

$$\varepsilon = \frac{\sigma}{E} + \left(\frac{\sigma}{K\prime}\right)^{n\prime} \tag{1}$$

The best fitting of the experimental data in figure 3 is given by E=15500 MPa, K’=54 MPa, n’=4.7 for the strain rate 1E-2 s-1 and E=15500 MPa, K’=53 MPa, n’=4.1 for the strain rate 1E-3 s-1. The specimens used for the fatigue testing were machined from high voltage subsea cable sheathing extruded to a thickness of 1.8 mm. The original curvature of the sheathing was kept, in order to increase buckling resistance and to avoid the introduction of additional forming of the sheath, obtaining specimens corresponding to the geometry in figure 1. The tests were performed in tensile- compression loading mode which corresponds to the loading mode in the sheathing when the cable is subjected to bending. All tests were conducted in air at room temperature with a Zwick/Roell LTM Electrodynamic machine equipped with a 10 kN load cell. Digital image correlation (DIC) technique was used to control the longitudinal strain range according to the procedure schematically reported in figure 2: the test was started setting the positions values calculated based on tensile properties of the material at the target strain rate. During the first cycles, DIC images were immediately post-processed to obtain the actual strain range values from the surface of the specimen. If the values obtained differed from the target strain range (with a tolerance of about 5%), the clamp position was adjusted and the control repeated. It is assumed that small adjustments done in the initial part of the specimen's fatigue life have negligible effect on the result. This correction of the imposed displacement was necessary due to the highly plastic behaviour of the material to account for the unavoidable clamping pressure. The use of DIC is preferred to the use of an extensometer because of the absence of contact with the specimen during testing which may create concentrators on the specimen's surface which will drive the fatigue crack initiation. However, it was not possible to execute real time DIC post processing and control the machine in closed loop without manual intervention. The tests were performed in strain control because of the plastic behaviour even at very low strain ranges. Plasticity is increased by a reduction of strain rate. The same characteristic would lead to the material permanently deforming and settling to a new length if a displacement ratio different from -1 was to be used. A total of 23 specimens were tested, 9 at 1E-3 s-1 and 14 at 1E-2 s-1, the results of which are reported in figure 4 in terms of cycles to failure vs longitudinal strain range, as computed by DIC in the central part of the specimen. Even if no strong stress-strain difference was detected in the tensile testing, time dependent damage is active and shows a different influence according to the strain rate: the increased duration of a cycle at 1E-3 s-1 compared to 1E-2 s-1 makes so that the former presents a reduced fatigue life than the latter in terms of cycles to failure. The observation of the evolution of the stress range in the initial part of the testing shows a negligible relaxation for the specimens tested at 1E-2 s-1, while a reduction of the stress range of more than 10 % happened only for two of the specimens tested at 1E-3 s-1, with the others showing limited relaxation as well. The difference detected is quantified in an increase of strain range from 2.46 % to 6.12 %. considering a 50 % failure probability at 2E-6 cycles. The reduction of resistance in terms of strain range is not constant, but inversely proportional to the load level: the fatigue curve slope is indeed 0.558 for 1E-3 s-1 and 0.346 for 1E-2 s-1 over the tested range.

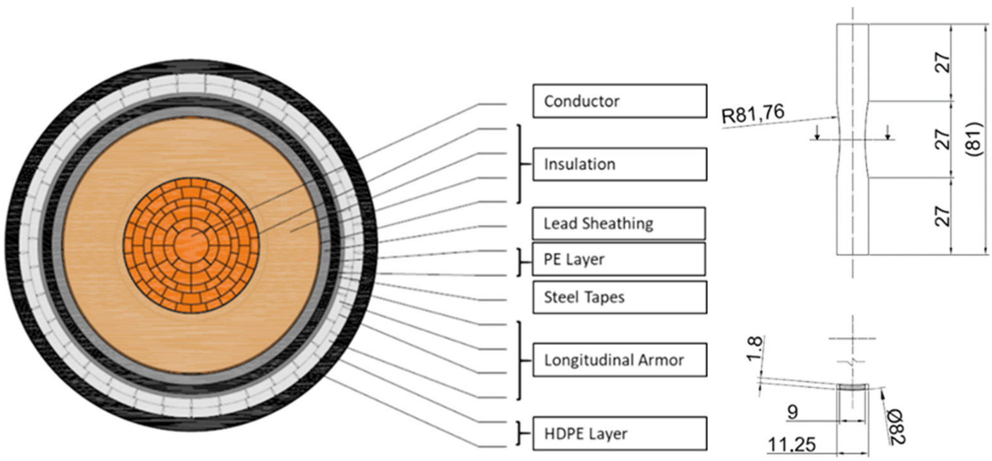

Fig. 1. Cable section scheme and fatigue specimen geometry. Longitudinal direction of cable and specimen correspond.

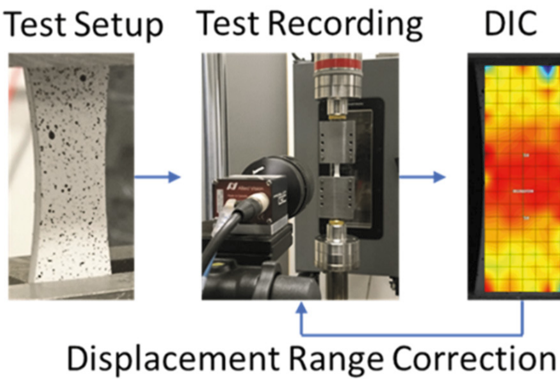

Fig. 2. Strain range control logic.

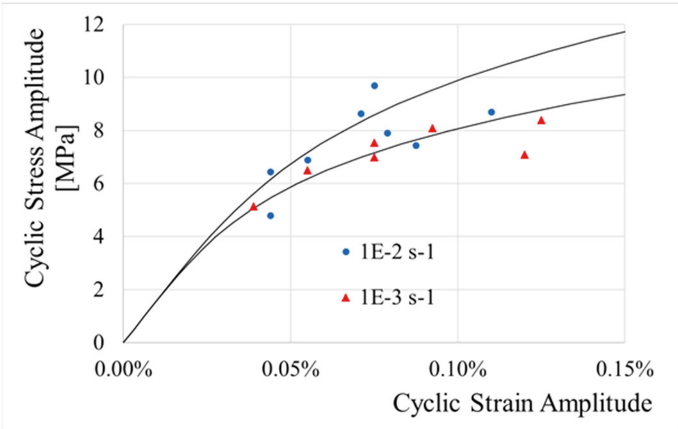

Fig. 3. Ramberg-Osgood best fit of cyclic properties.

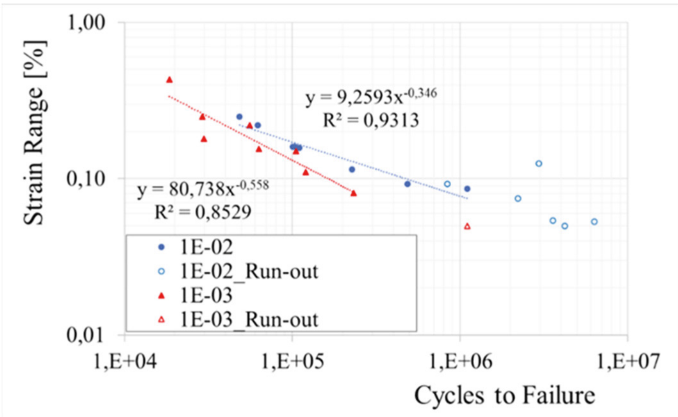

Fig. 4. Summary of fatigue results.

3. Fracture surface investigation

Post-mortem metallography and fractography through scanning electron microscopy (SEM) was performed in order to understand the dominant failure mechanism/s and with the perspective of developing adequate damage models for the prediction of the fatigue performance of the alloys of interest. The specimens of choice for the fracture analysis presented were fatigue tested in the two extreme conditions of the testing parameters ranges: the highest strain rate and strain range providing results for lower creep influence on one hand and the lowest strain rate and strain range on the other hand, being majorly affected by creep inherent damage. The two cases correspond to 0.25 % strain range, 1E-2 s-1 strain rate and 0.15 % strain range, 1E-3 s-1 strain rate respectively. Figures 5 and 6 show the results of metallographic investigation of the afore mentioned specimens. Metallographic investigations were performed on the longitudinal direction of the specimens. In addition, figures 7 and 8 show SEM imaging of the fractures in the same order. The samples were prepared following the same procedure developed for Viespoli et al. (2019). It is evident for both specimens that crack propagation is dominated by grain boundary failure. In addition, several fatigue cracks nucleated and propagated, indicating diffused damage and not only a single dominant fracture. Most cracks develop in secondary branches following the grain boundary morphology. This damage behaviour appears to be more relevant in the case of increased creep influence, see figure 6, and is, in any case, analogous with the behaviour of another lead alloy investigated by the authors Viespoli et al. (2019). The SEM imaging of the fracture surfaces reveal a mixed behaviour crack propagation: both intergranular and transgranular cracking are present for the two extreme testing conditions. In particular, figure 7 shows crack initiation by grain boundary failure and subsequent presence of both failure mechanisms after approximately 400 µm of penetration.

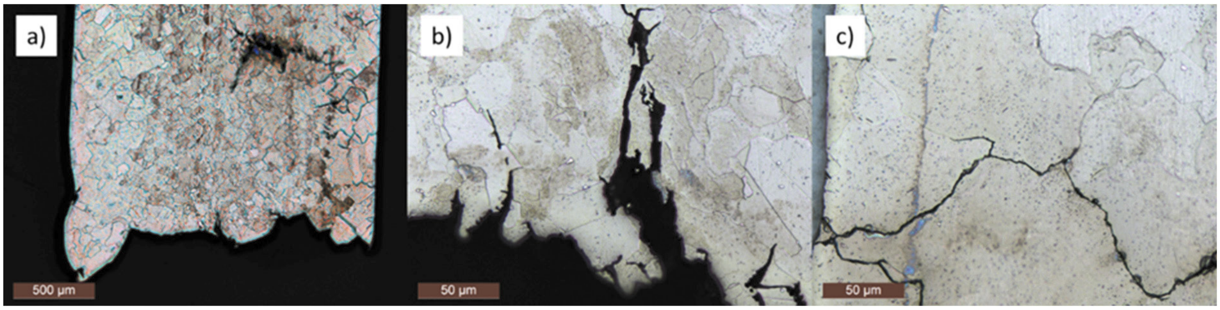

Fig. 5. Metallography of fatigue fracture: 0.25 % strain range, 1E-2 s-1 strain rate. Side view of the fracture (a). Details of secondary cracking (b, c).

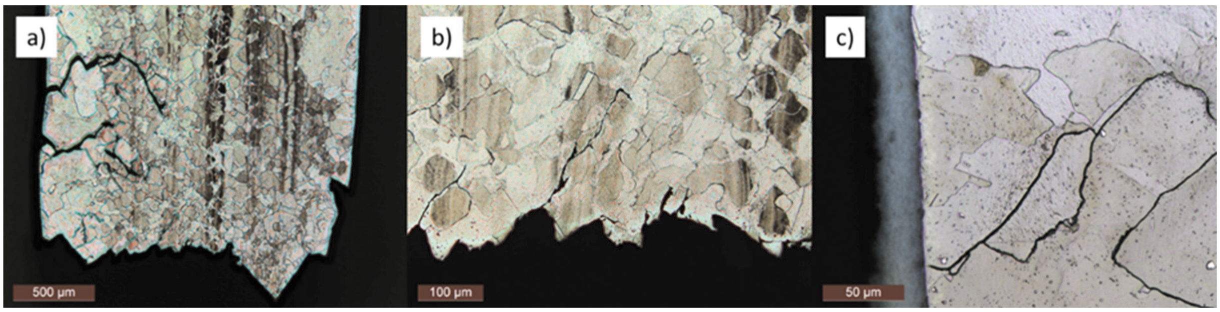

Fig. 6. Metallography of fatigue fracture: 0.15 % strain range, 1E-3 s-1 strain rate. Side view of the fracture (a), note multiple non-fatal cracks. Details of secondary cracks propagating at the grain boundaries at an angle of 45º from the pulling direction (b, c).

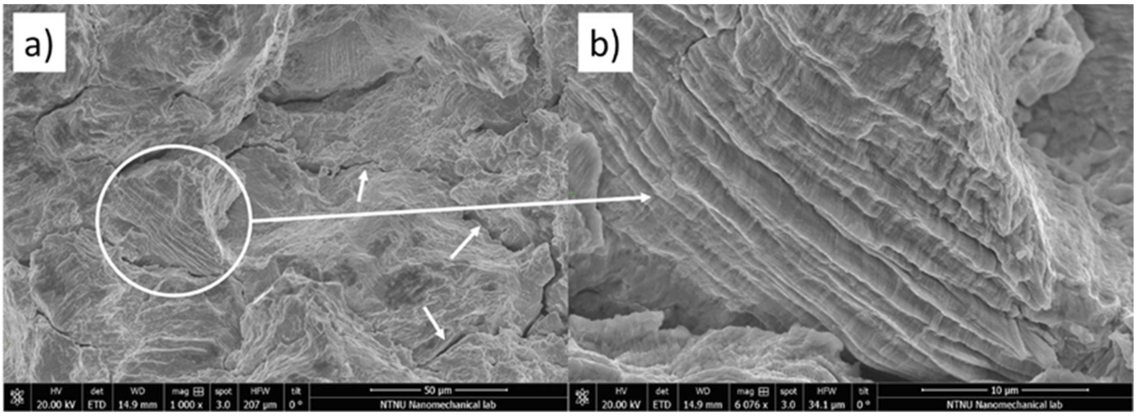

Fig. 7. Fracture of specimen tested at 0.25 % strain range, 1E-2 s-1 strain rate. Both intergranular (a) and transgranular (b) fatigue crack propagation are present.

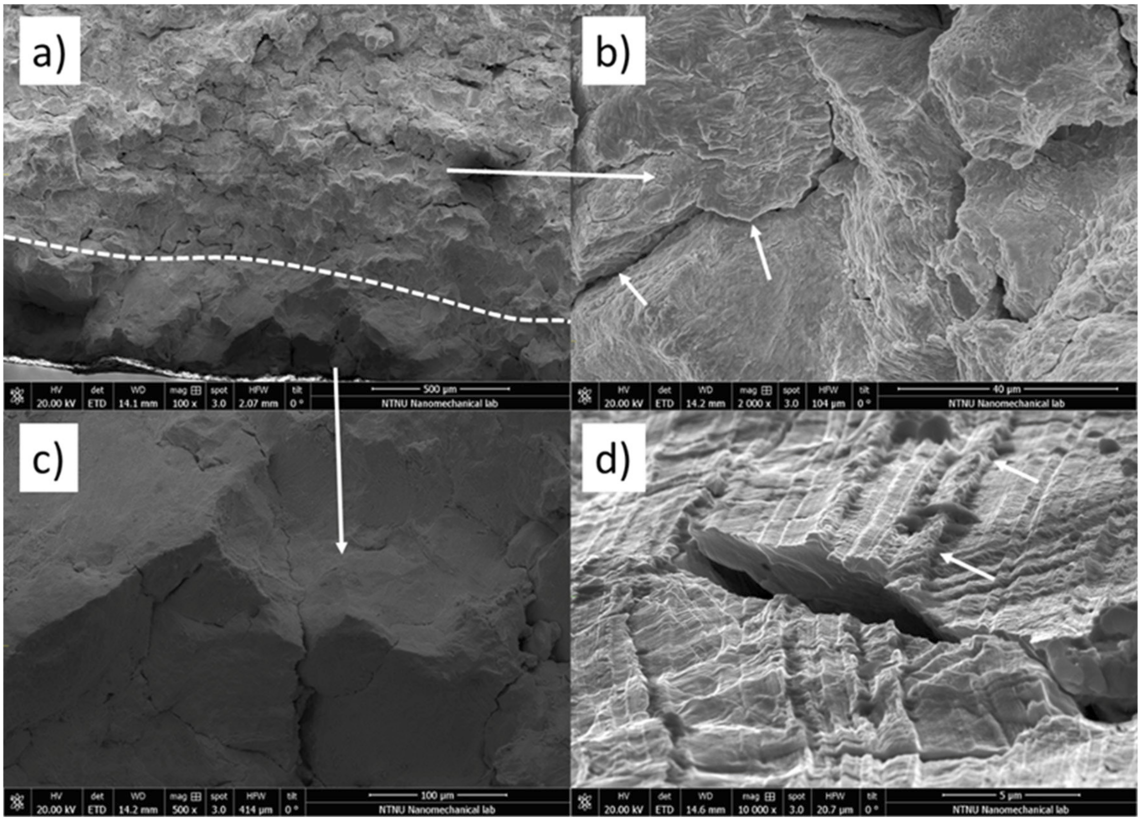

Fig. 8. Fracture of specimen tested at 0.15 % strain range, 1E-3 s-1 strain rate. The fatigue crack (a) is initially dominated by intergranular propagation (c) and then by a combination of intergranular and transgranular (b). Non-fatal secondary crack nucleated at the surface and extrusion grooves (d).

4. Discussion

Two series of Pb-Sn-Sb alloy (E- alloy) used for the production of subsea power cables were fatigue tested in air at room temperature in strain control at different strain rates to obtain an evaluation of the influence of stress dependent damage and investigate the consequent damage mechanics. The tests were performed by a Zwick/Roell LTM Electrodynamic machine equipped with a 10 kN load cell and the correctness of the imposed strain level was verified by DIC analysis on the central portion of the specimens. The results clearly showed an important influence of the strain rate on the fatigue performance due to the strong impact of time dependent deformation and damage already at room temperature. Previous work on a same alloy has been published by Anelli et al. (1988). In his work all tests were done at ambient conditions under reversed bending. Testing strain ranges and frequencies ranged down to approximately 0.10 % and 2 cycles/ h. The resulting frequency dependent fatigue model is readily available for fatigue calculations and often used as input data for such calculations for subsea power cables. Although the experimental methodology used in this work is different, it is clear that the 5 % probability of failure curve proposed by Anelli overpredicts the fatigue life by up to two orders of magnitude compared to the low strain range results presented by the authors. This difference appears to increase towards reduced strain range and rates. It is in other words highly critical to select an appropriate experimental approach as well as an accurate damage model. The abovementioned difference can in part be explained by the choice of loading mode which is consistent with the results presented by the authors in Johanson et al. (2019), which showed that the fatigue life of lead appeared to increase when tested by reversed bending compared to the tensile-compression loading mode, the latter being more representative of the actual loading mode the sheathing being subjected to in real cable operation. Another major difference between the results herby and those reported by Anelli lies in the adoption by the latter of a frequency corrected fatigue model to account for creep. It is important to notice that the strain rate will drop when shifting from higher to lower strain range at a given cyclic frequency. As already stated in a previous work by the authors, Johanson et al. (2019), it is suggested to adopt the strain rate rather than the frequency as central parameter when testing fatigue properties of materials for which time-dependent damage phenomena interact one another as in the case of lead in order to develop the base for an accurate mechanistically-based fatigue-creep damage model to adequately predict the lead sheath fatigue life for many operational scenarios. The fracture investigation, both by metallography of polished and etched samples at the height of the final fracture and by SEM imaging of the fracture surfaces, reveals how failure is dominated by grain boundary loss of cohesion at several points of the specimen. Creep characterization, implementation of opportune creep-fatigue interaction models for the prediction of the behaviour at very low strain rates, which are in fact representative of the operational conditions and development of alloys able to maintain elevated ductility, while reinforcing grain cohesion are important topics for research in the field. Ongoing work is directed toward overcoming some of these challenges.

5. Conclusions

The main conclusions on the fatigue testing performed on samples of lead E alloy subsea power cable sheathing can be summarized in the following points:

- The fatigue performance of the alloy is influenced by creep deformation. A shift of the strain rate causes an important shift in fatigue life in terms of number of cycles, with slower deformation causing cracking after fewer cycles.
- The crack propagation in lead is typically both intergranular and transgranular, with a lower strain rate increasing the formation of secondary cracks and having a detrimental impact on the grain boundaries.
- The development of a fatigue-creep interaction model based on the deformation and damage mechanisms active in the class of alloys of interest is a complex task, but necessary for a safe and knowledge-based prediction of the operational life of the components, whose real operating conditions are in fact dominated by low strain rates and elevated duration in terms of time.

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