Liquid Metal Embrittlement

Technical White Paper

SureScreen Scientifics

Description

Liquid Metal Embrittlement (LME) is an unusual and uncommon failure mechanism where a liquid metal can cause the rapid attack, usually along the grain boundaries, of another metal with a higher melting point when under stress, resulting in fast brittle fracture of an otherwise ductile material. Cracks can propagate through the material at speeds in the order of 10-100cm/s.

There are three main features that are generally considered to be accepted for the occurrence of LME: (1) that the metals have limited or no mutual solubility and a low tendency to form intermetallic compounds, (2) a certain critical stress is present and (3) that the liquid metal must be in direct contact with the solid metal at the atomic level. Furthermore, LME couples will also exhibit specific temperatures at which the behaviour of the solid metal changes from ductile to brittle.

Examples of LME ‘couples’ are;
• Steel-zinc
• Steel-copper
• Stainless steel-zinc
• Aluminium-mercury
• Nickel alloys-zinc
• Nickel steel-mercury

The three main features of LME listed above are, however, only empirical rules and with respect to point (1) and the list of the couples, steel and zinc do readily form intermetallic compounds and is one of the commonest cited forms of LME.

Mechanism

The mechanism involved in LME is not fully understood and various models have been proposed, but generally, LME produces a brittle and intergranular, or occasionally cleavage fracture, at reduced tensile stresses.

One proposed mechanism is that the surface energy of the solid metal at a crack tip is reduced by the effects of adsorption of the atoms from the liquid metal into the solid metal. The adsorbed atoms may reduce the strength of the atomic bonds leading to decohesion, and, hence cracking.

Another mechanism involves shear reactions at the crack tip. Adsorption of atoms from the liquid metal may cause reduction in shear and tensile cohesion and this can generate the development of dislocations and slip of the atomic planes. This then has the effect of increasing the plasticity of the material ahead of the crack tip and with sufficiently large strains, voids can be generated, and particularly at microstructural features such as defects, and precipitates. The fracture then proceeds by rapid ductile rupture.

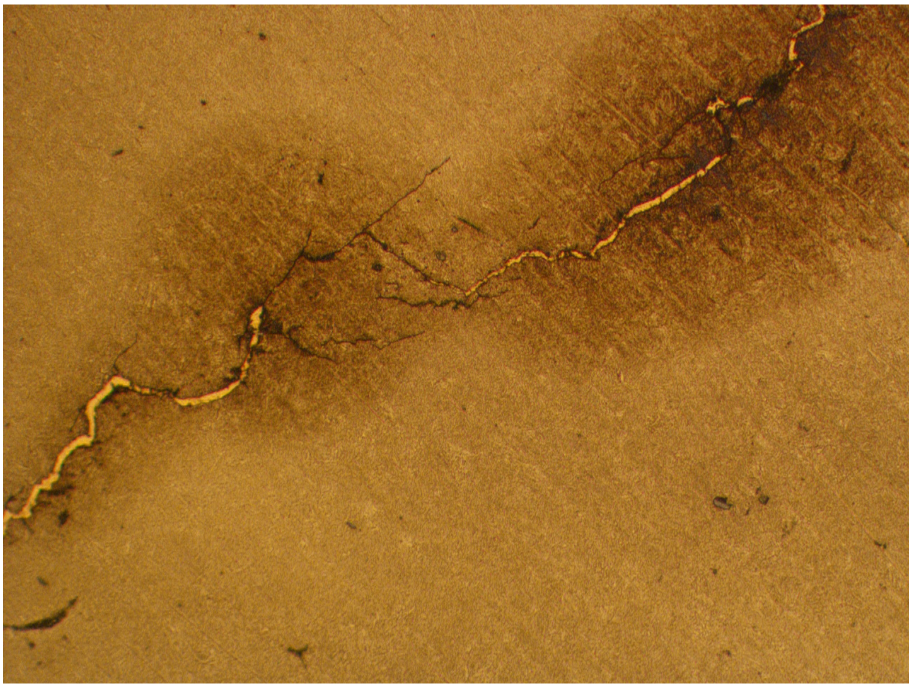
The risks of LME may be particularly important when considering use of materials exposed to high temperatures, sufficient to cause melting of one of the metals, and this is particularly so with welding. Steels are often coated in zinc to offer protection of the steel against corrosion. Removing all traces of zinc from the area to be welded, including the heat affected zone, should preclude the welding.

Welding copper to steel is not uncommon and is routinely carried out successfully without LME occurring. This demonstrates the important effect of stress on its development; the elimination of stress, either applied or residual, should avoid the potential for LME to occur in welded components or structures.

The handling of liquid natural gas (LNG) requires care with aluminium components as LNG can contain trace amounts of mercury; in 2004 the fire of an LNG plant in South Africa was attributed to LME from mercury traces in the LNG.

Appearance

LME fractures will inherently outwardly appear brittle. This may be in the form of intergranular or transgranular cleavage (decohesion model). At higher magnifications, some fractures may exhibit ductile dimpling (shear reaction model). In addition, fracture surfaces will often exhibit a thin coating of the embrittling (former liquid) metal as shown in the photomicrograph below of a section through a crack in a failed gear.



The gear was installed in a gearbox that suffered a failure of the lubrication system. Severe overheating of the copper-based bearings occurred, leading to the fracture of some of the gears by LME. This also demonstrates that the gear was particularly highly stressed.

Avoidance

A key factor in the avoidance of LME is in the awareness of its possibility, and then preventative measures can be taken. The reduction of stress in a material is significant, and can allow, for example, the welding of copper and steel components. Welding of steel with zinc coatings can be undertaken without the occurrence of LME, as with slow welding speeds the zinc will often burn off before it has a chance to cause cracking (the zinc burns off before the critical ductile-brittle temperature is reached) but reliance on the removal of the zinc from burning alone clearly introduces the potential for failure and particularly with high welding speeds or rapid thermal gradients. Appropriate welding procedures should then be followed to ensure all zinc is removed from the joint and potential areas of the heat affected zone. Failures by LME may also be a secondary, and unintended mechanism, such as with the example of the failed gearbox described above. The gearbox was failing anyway due to inadequate lubrication; LME of some of the gears just compounded the level of destruction. Some sources also cite LME as a factor in the explosion the occurred at Flixborough in 1975 where 28 people were killed; other factors such as stress corrosion cracking have also been blamed for the disaster, although the actual sequence of events and failure mechanisms has never been fully resolved.

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