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SPECIFICITY IN LIQUID METAL INDUCED EMBRITTLEMENT

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One of the most intriguing features of liquid metal induced embrittlement (LMIE) is the observation that some liquid metal–solid metal couples are susceptible to embrittlement, while others appear to be immune. This is referred to as the *specificity* of LMIE, and has been the subject of much research.

A number of theories have been developed in an attempt to predict the occurrence of LMIE in untested liquid metal–solid metal couples. These have mainly been based on two observations of embrittling couples, namely the low mutual solubility and the lack of intermetallic compounds between the solid and liquid metals [1]. A high mutual solubility may lead to dissolution of the solid metal in the liquid metal, which effectively blunts the crack tip and retards or arrests further crack growth [2].

The tendency for solid and liquid metals to react to form intermetallic compounds has been expressed in several ways. Westwood *et al.* [3] considered the difference in electronegativity values between solid and liquid metals, and found that in many cases the severity of embrittlement increased as the electronegativity difference decreased. Kelley and Stoloff [4] also developed a bond interaction–solubility model, and showed that, in general, couples with low mutual solubility and a high interaction energy are more susceptible to embrittlement. Numerous other models have also been developed, and these have been reviewed by Fernandes [5].

There are, however, many drawbacks associated with all of the models developed to date, not least of which is the failure to correctly predict embrittlement in all cases. A further drawback also becomes evident when considering the specificity data over a number of years. Since the 1960s [2], tables have been drawn up listing the couples which are known to fail by LMIE and those which appear to be immune to embrittlement. An example of this is given in Table 1. Analysis of the data presented in such tables shows that certain liquid metal–solid metal couples, which were initially recorded as being immune to embrittlement, were subsequently found to be very susceptible to LMIE using different testing procedures (e.g. the steel–lead couple [7]).

A probable explanation for the erroneous data in early studies is that such data were derived from tests employing, at best, a narrow range of test conditions. In view of the significant evidence now available that the severity of LMIE depends on such factors as temperature [8], strain rate [9], solid metal microstructure [10], and solid and liquid metal composition [11], the failure to observe embrittlement under a given set of conditions does not preclude embrittlement under different conditions. Furthermore, the vast majority of early LMIE studies employed simple tensile testing techniques using smooth specimens. In these tests, embrittlement was detected by a reduction in elongation to failure, in percentage reduction in cross-sectional area, or in true fracture stress. Furthermore, these tests depend on the conditions necessary for crack initiation (as opposed to propagation), and are valid over a limited range of test parameters, such as strain rate and temperature. The drawbacks

Table 1. Table of specificity data produced by Shunk and Warke [6]

	Liquid														
Solid	Hg	Cs	Ga	Na	In	Li	Sn	Bi	Tl	Cd	Pb	Zn	Te	Sb	Cu
Sn	X*														
Bi	X														
Cd	X	X	X				X								
Zn	X		X				X				X				
Mg				X								X			
Al	X		X	X	X		X			X		X			
Ge			X		X		X	X	X	X	X			X	
Ag	X		X			X									
Cu	X		X	X	X	X	?	X			X				
Ni	X					X	X				X				
Fe	X				X	X	X			X	X		X	X	?
Pd						X									
Ti	X									X					

*Embrittling couples.

of this approach are clearly illustrated by the results of recent tests carried out by the authors on the brass–gallium system.

Tensile tests on smooth, unnotched specimens were used to study the embrittlement of two brass alloys by molten gallium ($T_m = 29.8$ °C). The alloys used were CZ106, a 70/30 alpha-brass, and CZ109, a 60/40 alpha–beta brass. Both alloys were in the annealed condition. Tests were conducted over a range of temperatures and strain rates, both with and without molten gallium.

The results of the tests on CZ109 brass are shown in Fig. 1, where the percentage reduction in cross-sectional area at failure (%RA) is plotted as a function of temperature for various strain rates. It is clear that specimens tested without gallium show a gradual decrease in %RA with increasing temperature. Furthermore, the %RA is independent of the strain rate. In the case of specimens tested with gallium, a significant decrease in %RA is observed over a finite temperature range. This is referred to as a *ductility trough*, and its occurrence in LMIE under tensile testing conditions is well documented [12]. Moreover, the severity of embrittlement, as measured by the "depth" of the ductility trough, as well as the temperature range over which embrittlement persists, i.e. the "width" of the ductility trough, increases with increased strain rate. This again is in agreement with the published literature on LMIE [3, 13]. The embrittlement of specimens tested within the ductility trough was confirmed by scanning electron microscopy studies.

The results of the tests on CZ106 brass are given in Fig. 2, where again the %RA is plotted as a function of temperature for various strain rates. In this case, the %RA decreases gradually with increasing temperature for specimens tested both with and without molten gallium. A noticeable strain rate dependence is observed at high temperatures, where the

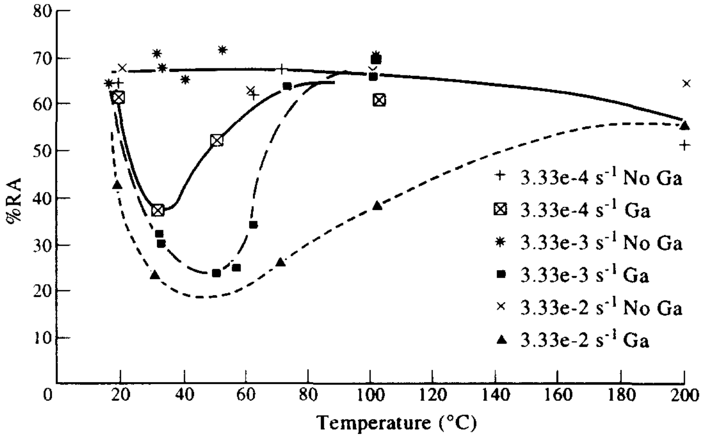

Fig. 1. Plot of %RA as a function of temperature at various strain rates for CZ109 brass.

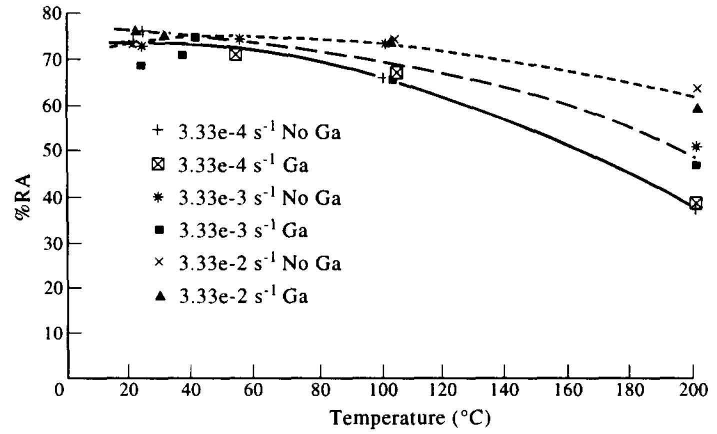

Fig. 2. Plot of %RA as a function of temperature at various strain rates for CZ106 brass.

%RA decreases as the strain rate decreases. However, the ductility trough observed in the case of the CZ109 brass is absent, and there is no evidence of embrittlement. This was confirmed by scanning electron microscopy studies of all the specimens tested. Based on these studies it could be implied that CZ106 brass is immune to LMIE by molten gallium, thus lending support to the concept of specificity.*

The failure to detect embrittlement in the CZ106 brass using smooth tensile specimens prompted the use of notched specimens. A shallow notch, approximately 0.25 mm in depth, was made at the centre of the gauge length of two CZ106 brass specimens, and these were subsequently tested both with and without gallium. In the latter, no significant difference was observed in the load elongation plot, and final failure was ductile. This can be expected since alpha-brass is not notch-sensitive. However, in the case of the specimen tested in gallium, significant embrittlement was detected. This was evident from the reduced plastic deformation accompanying failure and the large decrease in the true fracture stress from 950 MPa for the specimen tested without gallium to 300 MPa for the specimen tested in gallium. Scanning electron microscopy also showed distinct evidence of intergranular embrittlement (Fig. 3).

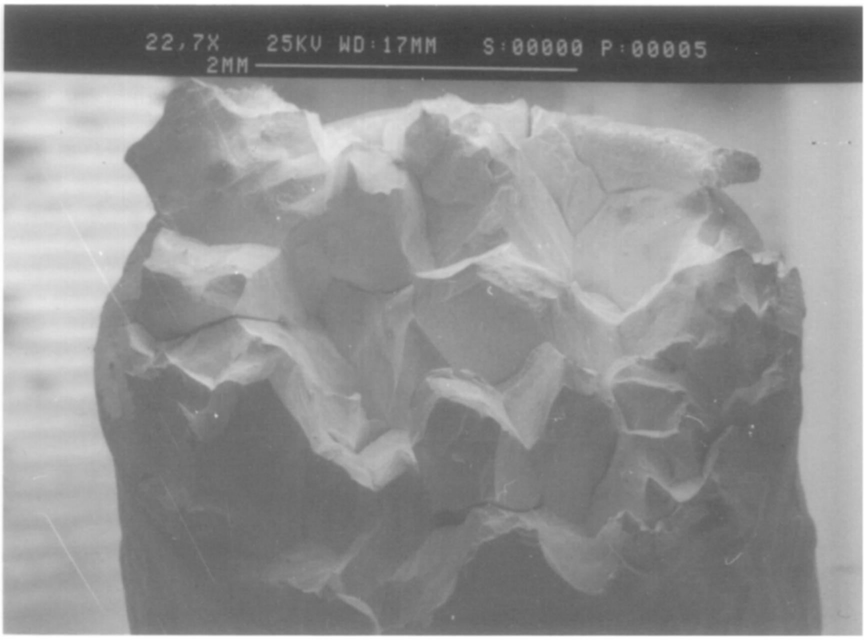

Fig. 3. Fracture surface of the notched CZ106 brass specimen tested in molten gallium.

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*The reasons for the differing behaviour of CZ106 and CZ109 brass in molten gallium will not be discussed in this article.

These results indicate clearly that CZ106 brass is, in fact, susceptible to LMIE given the appropriate testing conditions. Furthermore, subsequent tests on pre-cracked, fracture mechanics type specimens of CZ106 brass confirm that this material is susceptible to embrittlement in molten gallium [5].

The concept of specificity is based on the apparent immunity of some liquid metal–solid metal couples to LMIE, as determined by the absence of a ductility trough. However, the results of the present study, as well as an analysis of the literature, indicate that the presence of such a ductility trough depends strongly on the testing conditions and procedures employed. As such, it is questionable whether *specificity* is an intrinsic characteristic of the LMIE failure mechanism.

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