Continuous and discontinuous crack growth in brass embrittled by liquid gallium

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ABSTRACT: The mechanics of liquid metal induced embrittlement (LMIE) are not well understood and this phenomenon is of a high degree of industrial importance. Discontinuous and continuous crack propagation in gallium-embrittled brass was studied using double cantilever beam specimens and crack propagation was found to be discontinuous when the imposed crack speed was less than 6mm/s and was more or less continuous if greater. The threshold K for cracking was found to be non-unique in this system and was weakly dependent on testing variables such as crosshead speed. The discontinuous crack propagation and dependence on crosshead speed were attributed to the tendency of the cracks to blunten by a process of dissolution at the crack tip. A comparison of the experimental results with existing theory suggests that crack growth may not be solely controlled by supply of embrittler to the crack tip.

1 INTRODUCTION

Liquid metal induced embrittlement (LMIE) is the phenomenon where crack propagation is facilitated by the presence of a liquid metal in the crack. This phenomenon has been investigated for many years and a number of micromechanical models for LMIE fracture have been proposed, largely based on detailed fractographic studies (Kamdar (1983), Lynch (1988)). However, the mechanics of the propagation of LMIE cracks is still not fully understood, and a better understanding of the behaviour of these cracks has the potential to inform our understanding of the micromechanics of fracture. In this paper, the crack propagation behaviour of gallium-induced LMIE fracture in brass is investigated in order to establish the d*a*/d*t* *vs* K behaviour of this system. The aim of the paper is to establish a robust experimental protocol for determining d*a*/d*t* *vs* K behaviour of propagating LMIE cracks using a technique that attempts to impose a d*a*/d*t* regime on the cracks. The technique will use the property of double cantilever beam (DCB) specimens that an imposed crosshead rate should produce a stable and well-characterised d*a*/d*t* if it is assumed that crack growth occurs at a constant K. Even if the latter condition is violated, a careful analysis of the load-CMOD-time traces from the specimens should provide useful insight into the d*a*/d*t* *vs* K behaviour of the system.

LMIE is a form of environmental cracking, similar in some ways to stress corrosion cracking. A typical method used to describe environmental cracking is to develop crack speed (d*a*/d*t*) *vs* stress intensity (K) diagrams, but this has been done in only a few cases for LMIE (Kapp (1984), Speidel (1971), Wheeler and Hoagland (1986)). The work by Speidel (1971) and Kapp (1984) has suggested that the diagram for LMIE is frequently step shaped, with the crack speed jumping from zero to a speed of the order of 10mm/s once a threshold stress intensity is exceeded. Clegg (2001) has suggested that although in some cases the crack velocity may be controlled by the fluid flow in the crack, in others the crack speed may be significantly slower than that associated with supply of embrittler to the crack tip. Hence, measurement of the K dependence of d*a*/d*t* in LMIE may give an important insight into the mechanisms of transport of the embrittler to the crack tip and possibly of the mechanism by which fracture occurs. In this study the d*a*/d*t* *vs* K_I behaviour of the brass-gallium system has been characterised using short double cantilever beam (DCB) specimens at approximately 32°C.

Previous work has suggested that LMIE fracture does not occur until a critical threshold stress intensity is exceeded, K_{Ilme}. Once this threshold is reached, the crack speed jumps to a relatively high value. This conclusion has been reached on the basis of experiments where cracks were allowed to propagate and arrest under conditions of decreasing stress intensity where crack speed was measured. In this study, the crack speed was controlled by controlling crosshead rate in the experiment on the assumption that cracking occurred at a constant K.

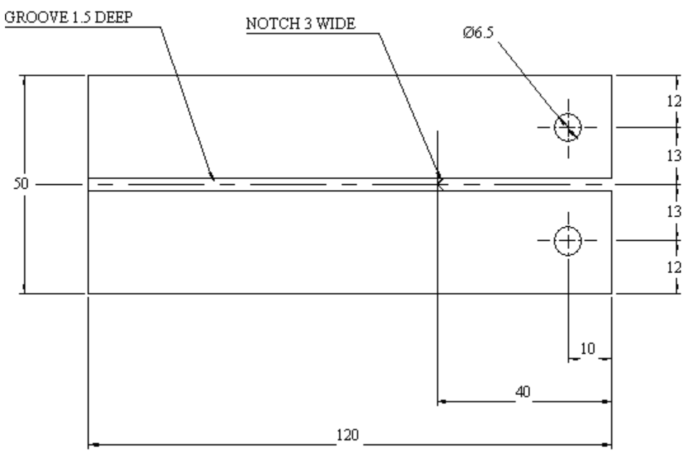

Figure 1 Dimensions of short DCB specimens.

Because of the mechanics of the specimens, *da/dt* was to some extent "imposed" on the specimens, with K being the measured variable. From the crack length and load on the specimen, the actual stress intensity at which cracking was occurring could be determined. By using slow crosshead speeds it was therefore possible to study the d*a*/d*t* *vs* K dependence at crack speeds lower than the threshold crack speed.

2 EXPERIMENTAL PROCEDURE

The material used in these experiments was BS2874 CZ121. This is a cold rolled, leaded brass with a nominal composition of 58Cu 39Zn 3Pb. The material was supplied as strip, with cross sectional dimensions of 50 × 12.5mm (2inch × 1/2inch). From this strip, double cantilever beam specimens were made using the full thickness of the strip and the dimensions as shown in Figure 1. Side grooves were used to keep the crack straight during propagation. The specimens were fatigue pre-cracked with liquid gallium present at the tip of the crack, in a manner described previously (Clegg and Jones (1994)). Pre-cracking has been found to be difficult in LMIE cracks. Fatigue crack initiation often needs similar load ranges to cause initiation in LMIE cracks and once initiated, these cracks can run away to complete failure of the specimen if the crack is not arrested. Furthermore, it is difficult to complete pre-cracking at ΔK values below 60% of the K_{Ilme} for LMIE, as is normally suggested for K_{IC} testing. In this study, once the cracks were initiated, K_{Ilme} and *da/dt* measurements were made on propagating cracks or cracks that had recently arrested and were re-initiated.

Testing was carried out in a stiff (screw driven moveable crosshead) testing machine (Instron 1185) using a CMOD gauge. A variety of crosshead speeds were used and these are shown in Table 1. Periodically, the crosshead was reversed and the compliance of the specimen was determined in order to establish crack length. A crack length *vs* CMOD compliance curve was determined experimentally prior to testing and close agreement was found between the experimentally determined compliance curve and that found in the literature (Kanninen (1973)). Stress intensity was calculated using the following equation from Kanninen.

$$K = \frac{2\sqrt{3}Pa}{B^*\sqrt{h^3}}\left(1 + 0.639\left(\frac{h}{a}\right)\right) \qquad (1)$$

where K is the stress intensity, P is the load, *a* is the crack length, B^* is the effective thickness of the specimen and h is half the height of the specimen.

3 PREDICTION OF CRACK VELOCITY FROM COMPLIANCE CONSIDERATIONS

In the experimental design, one of the aims of the experiments was to try to impose a *da/dt* regime on the specimen and measure K. In the design of the experiments, an initial assumption was made that the cracking occurred once a threshold K value was exceeded and that the cracking was fast enough to occur at that rate. If it is assumed that cracking only occurs at one stress intensity, it is possible to use the compliance equation for the specimen and the equation for stress intensity (Eq. (1) above) to predict the average d*a*/d*t* throughout a test. Compliance can be determined from the equation in Kanninen.

$$C(a) = \frac{\Delta}{P} = \frac{4a^3}{E^*B^*h^3}\left(1 + 1.92\frac{h}{a} + 1.22\left(\frac{h}{a}\right)^2 + 0.39\left(\frac{h}{a}\right)^3\right)$$

$$= \frac{4}{E^*B^*h^3}\left(a^3 + 1.92ha^2 + 1.22h^2a + 0.39h^3\right) \qquad (2)$$

where Δ is the load line displacement of the specimen in mm, *P* is the load in N and E^* is the effective Young's Modulus of the material.

From the compliance curve and equation for stress intensity, we can predict crack speed for different crosshead speeds. *C(a)* can be differentiated with respect to time, *t*

$$\frac{\dot{\Delta}}{P} - \frac{\Delta}{P^2}\dot{P} = \frac{\partial C}{\partial a}\dot{a} \qquad (3)$$

where the dot over the variable indicates the derivative with respect to time. If we assume that K does not vary with time and crack speed, then we can differentiate Eq. (1) with respect to time, and from this, crack speed as a function of crosshead speed can be estimated for a perfectly stiff machine.

$$\dot{a} = \frac{\dfrac{2\sqrt{3}\dot{\Delta}}{KB\sqrt{h}}\left(\dfrac{a}{h}+0.639\right)^2}{\left(\dfrac{\partial C}{\partial a}\left(\dfrac{a}{h}+0.639\right)-\dfrac{C}{h}\right)} \quad (4)$$

This can be modified to incorporate the compliance of the testing machine and load train, K_m where,

$$k_m = \frac{\Delta_m}{P} \quad (5)$$

where Δ_m is the extension of the machine only due to a load, P. Therefore, the crosshead movement, Δ_T will be determined by

$$\Delta_T = \Delta + \Delta_m = P(k_m + C) \quad (6)$$

Therefore, the crack speed in a testing machine of finite compliance is given by,

$$\dot{a} = \frac{\dfrac{2\sqrt{3}\dot{\Delta}}{KB\sqrt{h}}\left(\dfrac{a}{h}+0.639\right)^2}{\left(\dfrac{\partial C}{\partial a}\left(\dfrac{a}{h}+0.639\right)-\dfrac{C+k_m}{h}\right)} \quad (7)$$

From Eq. (7), it can be seen that if cracking begins at one stress intensity, then by imposing a certain crosshead speed, the crack will propagate at a predictable average speed. The crack speed is, however, dependent upon crack length, a.

4 RESULTS

A number of crosshead speeds were imposed on the specimens in order to produce a range of predicted average crack speeds. These crack speeds are calculated using a measured machine compliance, k_m, of

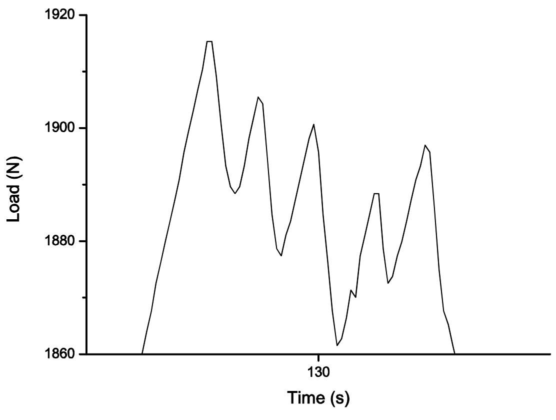

Figure 2 Typical load *vs* time trace during one of the cracking events, showing propagation/arrest behaviour.

6.9×10^{-5}mm/N and are shown in Table 1. As can be seen, the imposed crack speeds covered from 6.5×10^{-2} to 6.5×10^{1}mm/sec. The behaviour appeared to fall into two major types. At low imposed crack speeds the crack repeatedly propagated and arrested. This can be seen on the load *vs* time trace shown in Figure 2. At higher imposed crack propagation rates, cracking occurred continuously; often continuing after the crosshead of the testing machine was stopped or reversed.

Table 1 Predicted crack speed as a function of crosshead speed.

Crosshead speed (mm/min)	Predicted crack speed (mm/sec) at 40mm	at 50mm	at 60mm	at 70mm
0.05	0.16	0.12	0.08	0.07
0.1	0.32	0.24	0.17	0.13
0.2	0.65	0.47	0.34	0.26
0.5	1.62	1.19	0.85	0.65
1	3.24	2.37	1.69	1.30
2	6.47	4.74	3.38	2.61
5	16.2	11.9	8.45	6.52
10	32.4	23.7	16.9	13.0
20	64.7	47.4	33.8	26.1

At low crosshead speeds, crack propagation did not occur until a critical stress intensity was exceeded and then occurred at a relatively fast rate until the crack arrested. Crack extension in DCB specimens at constant CMOD is accompanied by a decrease in load and once the stress intensity decreased below the critical value, the crack arrested. Continued crosshead movement increased the stress intensity again until it reached a critical value and propagation occurred again. This “stick-crack” type of propagation occurred at relatively regular intervals, as shown Figure 2. In none of the experiments was any cracking detected before the stress intensity to cause fast fracture was reached. Typically, the crack would extend 0.5 to 1 mm before it arrested. Crack velocity was measured by estimating the crack extension that occurred between each propagation/arrest event and dividing that by the time taken. Crack length was determined using the compliance of the specimen and the individual crack extensions were estimated by dividing the crack extension between two compliance measurements by the number of propagation/arrest events between compliance measurements, usually four or five.

Within each of the tests, the stress intensity to initiate crack propagation and the stress intensity at crack arrest were found to be the same within experimental error. However, between tests, it was not possible to establish a unique K_{Ilme}. Figure 3 shows a plot of the initiation and arrest stress intensities as a function of crosshead speed. In the stick-slip experiments, initiation and arrest stress intensities decrease slightly as the crosshead speed is increased. However, the crack velocity during the propagation phase was approximately 6 ±3mm/sec. This appeared to be independent of crosshead speed and a plot of crack speed as a function of threshold stress

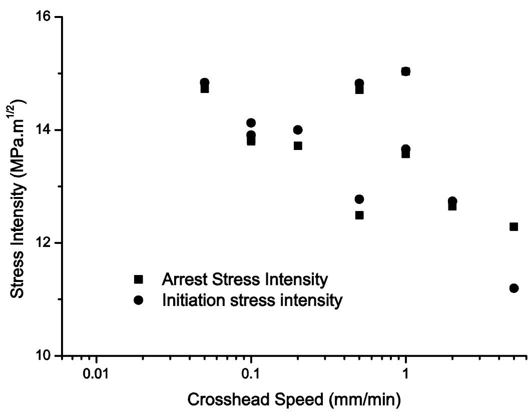

Figure 3 Effect of crosshead speed on initiation and arrest stress intensities.

intensity can be seen in Figure 4.

At crosshead rates of greater than 5mm/min, the cracks propagated continuously until the crosshead was turned off. From Table 1, this corresponds with a crack speed of approximately 10mm/s. If the imposed crosshead speed was such that the predicted *da/dt* was greater than 6mm/sec, the stress intensity on the crack continued to rise once the crack had initiated. This can be seen in Figure 5. When the crosshead was reversed, as was done in Figure 5, the stress intensity was higher than the initiation/arrest stress intensity and although it continued to propagate, the crack decelerated until it arrested. A *da/dt vs* K graph during one of these events (corresponding to that in Figure 5) is shown in Figure 6. Figure

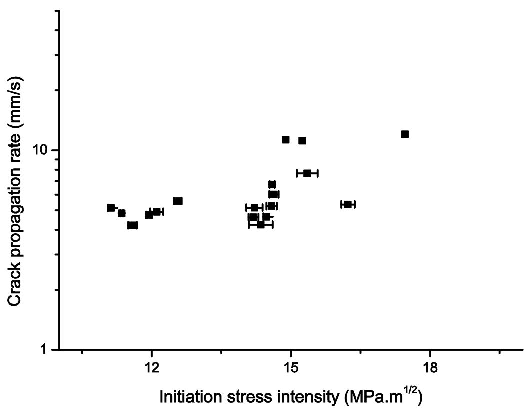

Figure 4 Average *da/dt vs* initiation K diagram for brass embrittled with gallium (summary chart). Error bars represent one standard error.

6 shows a prediction of *da/dt vs* K based on the rate of supply of embrittler to the crack tip using the modeling developed in Clegg (2001).

5 DISCUSSION

Two modes of behaviour were found in these experiments. The type of behaviour that occurred was dependent upon the crosshead speed chosen, and thus the average crack speed imposed on the specimen. When the imposed crack speed was lower than 6mm/s, cracking occurred in a jerky fashion. That is, the crack did not propagate until a critical stress intensity was exceeded and once initiated, cracking occurred at a relatively fast rate of approximately 6mm/sec. If the imposed crack speed was greater than 6mm/s, cracking occurred continuously.

At low crosshead speeds the cracks only propagated once a threshold stress intensity was exceeded. As the crack grew longer, the compliance of the machine increased and therefore for a quasi-static CMOD, the load and thus stress intensity on the crack decreased. The stress intensity eventually decreased until it fell below a certain value at which the crack arrested. As the crosshead continued to move, the stress intensity increased again until the threshold was exceeded and crack propagation occurred once again (see Figure 2). This meant that the imposed crack speed was achieved by the average of periods of crack propagation interspersed by periods of crack arrest.

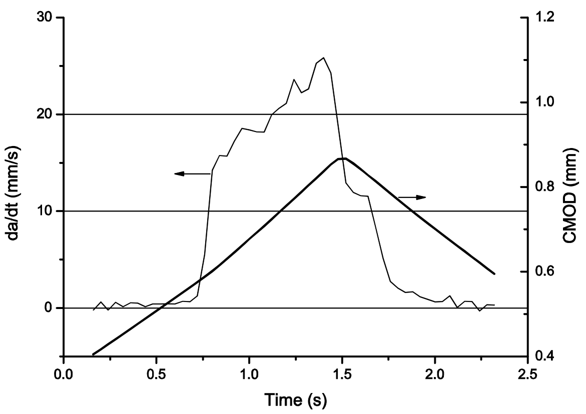

Figure 5 Crack speed and CMOD rate *vs* time for a cracking event at a driven crack speed of over 6 mm/s.

Typically, "stick-crack" behaviour such as this occurs in systems such as polyester and epoxy resins whose crack tips blunten and re-sharpen and in certain steels whose fracture toughness decreases as the crack velocity increases and the stick-crack behaviour may be accounted for in this system by a similar mechanism. It has been postulated that dissolution of the brass by the gallium may retard crack propagation. Fernandes and Jones (1995) found that gallium embrittled cracks in brass arrested more readily under fatigue conditions as test temperature increased and attributed this to blunting of the crack tip due to dissolution. A possible reason for the stick-crack behaviour of this system is that once the crack arrested, it bluntened slightly as a result of stress-assisted dissolution of brass by gallium.

Therefore, to continue cracking, a higher stress intensity than the arrest stress intensity must be achieved before fracture recommenced. Fracture then occurred until the stress intensity once again fell below the arrest stress intensity. Although in these experiments there appeared to be no difference in initiation and arrest stress intensities, the spread in K between initiation and arrest may be less than experimental error. In the stick-crack region of behaviour, as the crosshead speeds increase, the initiation and arrest stress intensities decrease slightly. The decrease in initiation K supports the theory that the stick-slip phenomenon is due to dissolution and

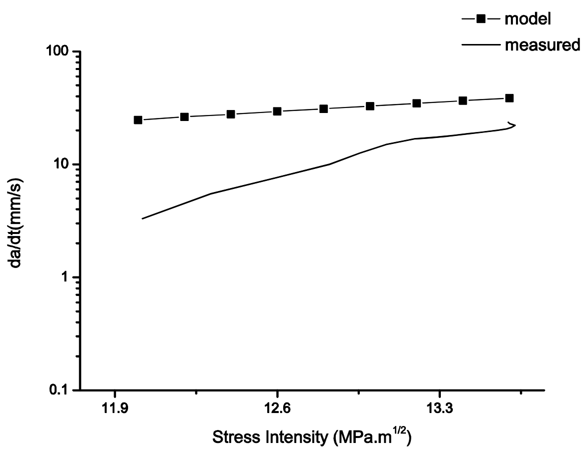

Figure 6 *da/dt vs* K diagram for specimen shown in Figure 5, above with the predictions of rate of supply of embrittler based on Clegg (2001). Increasing load curve only shown.

blunting at the crack tip when the crosshead speeds are slow. However, the decrease in arrest K is more difficult to explain. The results shown in Figure 3 indicate that the threshold stress intensity is non-unique for this system and dependent on crosshead speed. Other workers have also found that K_{Ilme} is non-unique. Wheeler and Hoagland (1986) found that K_{Ilme} in mercury embrittled Al-7075 varied from approximately 5.5 to 9 MPa√m depending on the testing conditions. In this case, the non-unique behaviour of the LMIE cracks was attributed to uncontrolled oxidation of the crack tip. Undoubtedly, this is an area that warrants further research.

In the experiments carried out here, the *da/dt vs* K curve for propagating cracks does appear to be reasonably independent of the experimental conditions, at least in the relatively narrow range of conditions encountered here. Figure 4 shows a plot of *da/dt vs* K_{Ilme} for a range of conditions and shows that although the K_{Ilme} is not unique for this system, the *da/dt* values once the crack is initiated are relatively consistent. The *da/dt* values shown in Figure 4 are average values of crack propagation determined over cracking events which may last for only 1 mm. This may explain discrepancies between Figure 4 and Figure 6, which is determined for a propagating crack. The modeling of Clegg (2001) suggests that crack propagation rates are dependent upon experimental conditions such as geometry and crack length, but that has not been fully investigated here.

If the crack speed imposed on the specimen (see Eq.(7)) was greater than 6mm/sec, cracking still occurred at a relatively slow crack speed. As a result, the stress intensity to cause cracking increased above the threshold value, as the crack was being forced to propagate at a higher speed. Once the crosshead reversed or was stopped, there was sufficient stored energy in the specimen to continue cracking for some time until the K dropped below the arrest K. The model developed by Clegg (2001) to predict *da/dt* on the basis of the supply of liquid metal has been applied to this system and is shown in Figure 6 along with some of the measured data. The shape of the experimental *da/dt vs* K curve was similar to that proposed by Clegg (2001), but the values of *da/dt* for the experiments were approximately 1/10 of the predicted values. This may be due to inaccuracies in the modeling. However, it may also indicate that the crack propagation rate is not controlled by supply of embrittler to the crack tip alone.

6 CONCLUSIONS

Crack propagation in gallium embrittled brass was found to be discontinuous when the imposed crack speed was less than a critical value. If the impose crack speed was greater than 6mm/s then the crack speed was more or less continuous and increased slightly with increasing K. The threshold K for cracking was found to be non-unique in this system and was weakly dependent on testing variables such as crosshead speed. The discontinuous crack propagation and dependence on crosshead speed were attributed to the tendency of the cracks to blunten by a process of dissolution at the crack tip. Crack speeds were approximately 1/10 of the rate of supply of embrittler as predicted by Clegg (2001) and this may indicate that crack propagation is not solely controlled by the supply of embrittler to the crack tip.

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