Study on Liquid Metal Embrittlement of Carbon Steels (Report 2)

–Effect of Erosion of Carbon Steel in Liquid Metals on LME–

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Abstract

LME aspects of carbon steels in liquid Cd-Zn alloy environments were investigated under the changes in temperature by constant strain rate test. From these results, the carbon steels in liquid Cd-5Zn alloy were almost immune to LME at higher temperature, whreas those in liquid Cd-50Zn alloy were severely embrittled with increasing temperature. In the latter case, it was confirmed that LME sensitivity of carbon steels shows the different behavior in three temperature regions. Furthermore, it was shown that LME behavior was related to the erosion behavior of iron by liquid zinc.

KEY WARDS: (Liquid metal embrittlement) (Temperature) (Erosion) (Carbon steel) (Cd-Zn alloy)

1. Introduction

In the previous paper[1)], it was shown that grain boundary penetration induced a liquid metal embrittlement, that is LME, of carbon steels under an appropiate tensile stress when wetted with liquid Cd-Zn alloy. It was also demonstrated that LME sensitivity of steel could be evaluated by mean penetration lenghth at fracture. However, it is important to investigate the temperature dependence on LME behavior because it does not only permit us to understand the property of materials in liquid metals but also to elucidate the mechanism of LME.

So far, it has qualitatively reported that temperature can lower the susceptivility to LME by increasing ductility of solid metals, dissolving the crack tip part in liquid metal environment and so on[2)]. Hence, such aspects of the temperature for LME have not always been confirmed and have not discussed in detail, especially for carbon steel/ liquid Cd-Zn alloy couple.

In the present work, the temperature dependence of LME of carbon steels was studied in liquid Cd-Zn alloys and liquid Cd under the constant strain rate using an Instron-type tensile testing machine. The sensitivity of LME in different temperatures was evaluated by means of the time to fracture, maximum load and also the mean penetration length at fracture denoted in our previous paper. Moreover, LME aspects in this experiment were discussed on the basis of erosion results of iron in liquid zinc[3)].

2. Experimental Procedure

Solid materials used for LME tests are three kinds of carbon steels: SS34(0.066%C), S25C(0.28%C) and S45C (0.470%C), respectively. As liquid metals, Cd and Cd-Zn alloys were used in this work. Dimension of notched tensile test specimen and experimental methods are descrived in detail in the previous paper. LME tests of steels have been also performed in liquid metal environments and in air in the temperature range from 320 to 600°C. The maximum temperature (600°C) in this experiment is the same with the annealling that of carbon steels to remove any residual stress.

3. Results and Discussion

3.1 Effect of temperature on maximum load of LME

Figure 1 shows the typical flow curves in the case of 0.066%C steel embrittled by liquid Cd-5Zn alloy. Moreover, this also shows a result of temperature dependence without liquid metal. From this figure, the flow curves of 0.066%C steel in contact with liquid metal are slightly altered from that in air by the grain boundary penetration of liquid metal at 350° and 400°C as shown in previous paper. However, the tendency is not clear at 500°C and in order to know clearly the susceptibility for LME under the change in temperature, the authors adopted the maximum load at the fracture as an evaluation of LME.

The plots of the data of the maximum load presented in Fig. 1 as a function of temperature are shown in **Fig. 2**

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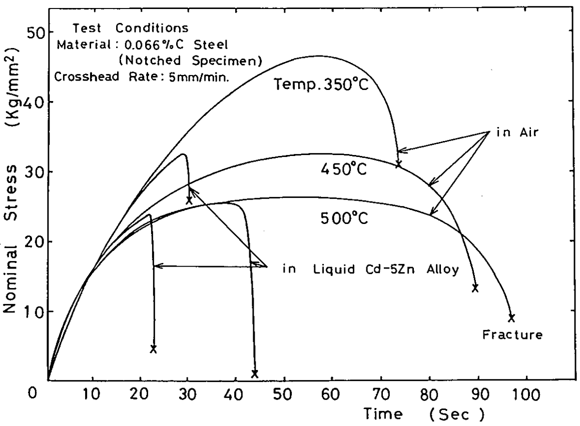

Fig. 1 Effect of LME of stress-time diagrams

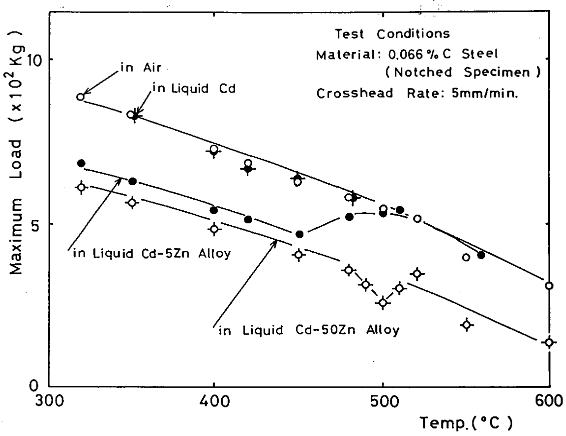

Fig. 2 Temperature dependence of maximum load of steel in contact with liquid metals

including results of liquid Cd-50Zn alloy. It is shown that liquid Cd is almost immune to LME of 0.066%C steel from this figure. From this figure, in 0.066%C steel/liquid Cd-5Zn alloy couple, the maximum load decreased with the increase of temperature below 450°C, but increased above 450°C and reached to that without liquid metal at 500°C. However, for liquid Cd-50Zn alloy, it decreased with increase of temperature to 600°C.

In the next section, in order to know the LME behavior, the authors discuss in detail it, using the mean penetration length given by the data of maximum load of steel with and without liquid metals in Fig. 2, as shown in the previous paper.

3.2 Temperature dependence of mean penetration length

According to the discussion in the previous paper, the mean penetration length, $\bar{L}_P$ is given by

$$\bar{L}_P = r_o - \bar{r} \qquad (1)$$

where r_o is the radious of the original tensile specimen and $\bar{r}$ is the mean radius of the part unaffected by LME. However, when the specimen is subject to the large plastic deformation, the equation must be modified to $r_o = r$, where r is the bottom radius of the notched specimen broken in contact with liquid metal.

The relation between test temperatures and the modified mean penetration length is shown in **Fig. 3**. From this

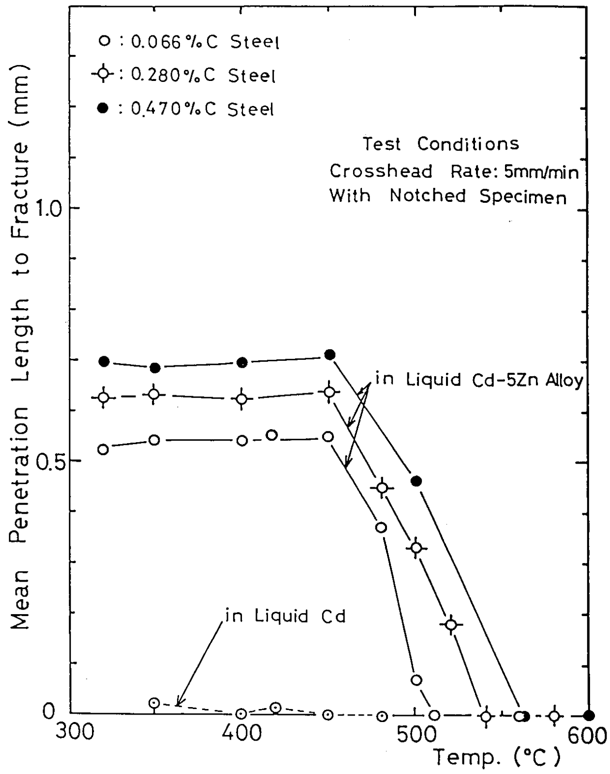

Fig. 3 Relation between temperature and mean penetration length to fracture by liquid Cd-5Zn alloy

figure, the mean penetration length of the liquid Cd-5Zn alloy into the 0.066%C steel is indicated to be constant in the temperature range 320 to 450°C. However, it decreased with an increase of temperature above 450°C and became 0 mm at 510°C. This means that LME of this steel is not observed above 510°C. In the case of liquid Cd, 0.066%C steel is not almost embrittled in the temperature range of this experiment.

Figure 4 shows the relation between temperature and mean penetration length of fracture induced by a liquid Cd-50Zn alloy. In this case, we can see that the mean penetration length into the various carbon steels shows different temperature dependence in three ranges of temperature respectively. Moreover, it was shown that the mean penetration length at fracture induced by the liquid Cd-50Zn alloy increases with the increase of the carbon content of steel. These results suggest that it is difficult to discuss the sensitivity of LME under the change in temperature only by the mean penetration length, because the mean penetration length at fracture does not change in

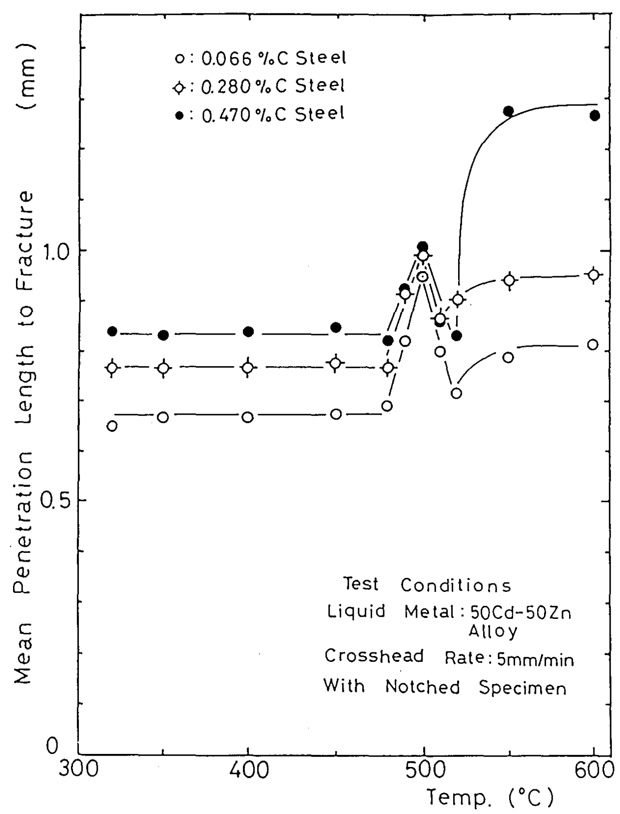

Fig. 4 Relation between temperature and mean penetration length to fracture by liquid Cd-50Zn alloy

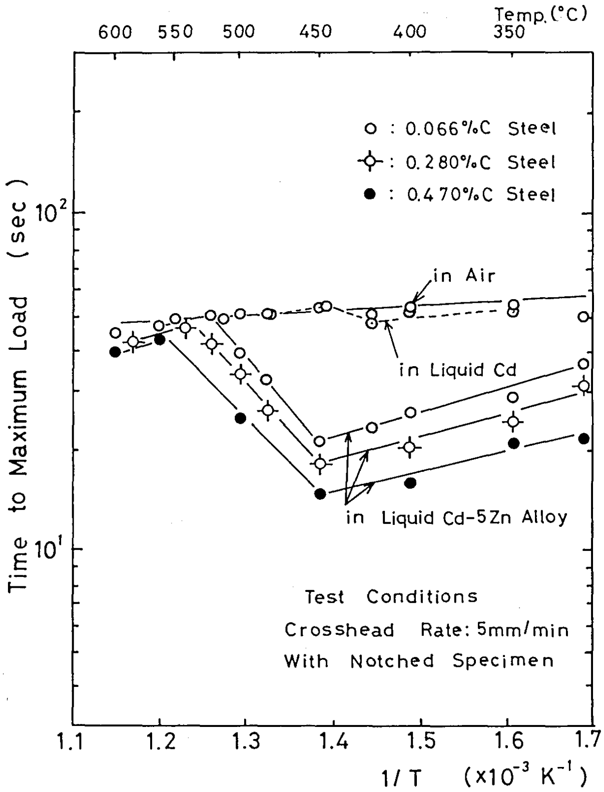

Fig. 5 Relation between temperature and time to maximum load (in liquid Cd-5Zn alloy, Cd and in air)

spite of the promotion of LME with increasing temperature. So, the mean penetration rate should be introduced in order to evaluate the sensitivity of LEM.

As the time to fracture is an important factor in LME, the authors show the time to maximum load of LME in next section.

3.3 Time to maximum load of LME

Figs. 5 and 6 shows the relation between temperature and time to maximum loads of various carbon steels respectively in liquid Cd-5Zn alloy, liquid Cd-50Zn alloy and liquid Cd. From these results, it is shown that a semilogarithmic plot of time to maximum load vs. the inverse of the absolute temperature (1/T) have remarkably good linear relationships in the ranges of temperature where the mean penetration length at fracture is constant for liquid alloy, as shown in Figs. 3 and 4. Thus, LME in this experiment may be controlled the grain boundary penetration induced by erosion process of carbon steel in contact with liquid metal. So, a typical result of 0.066%C steel embrittled in contact with liquid Cd-50Zn alloy at 450°C is shown in **Fig. 7**. It is observed that the erosion of iron in liquid Cd-50Zn alloy occurs at the solid-liquid interface.

From above results and discussion, the grain boundary penetration of liquid Cd-Zn alloys by means of Arrhenius reaction rate law would be considered. The Arrhenius law

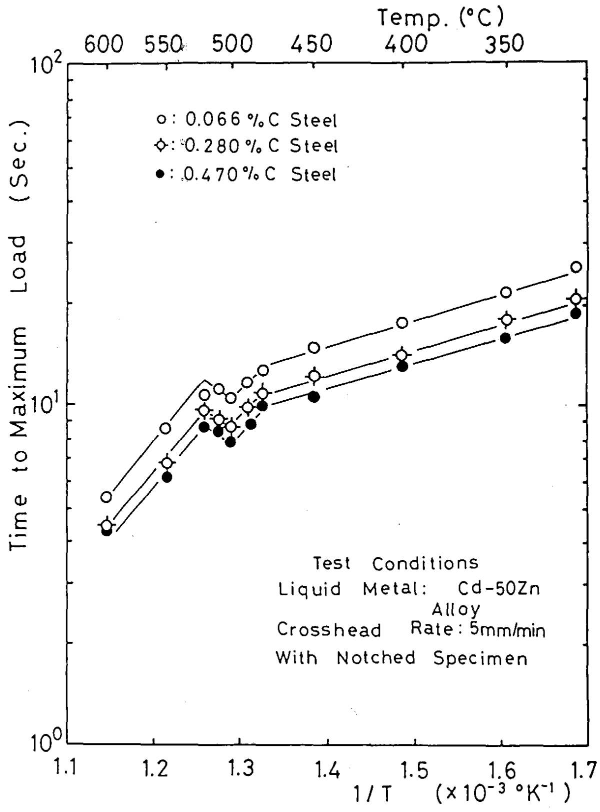

Fig. 6 Relation between temperature and time to maximum load (in liquid Cd-50Zn alloy)

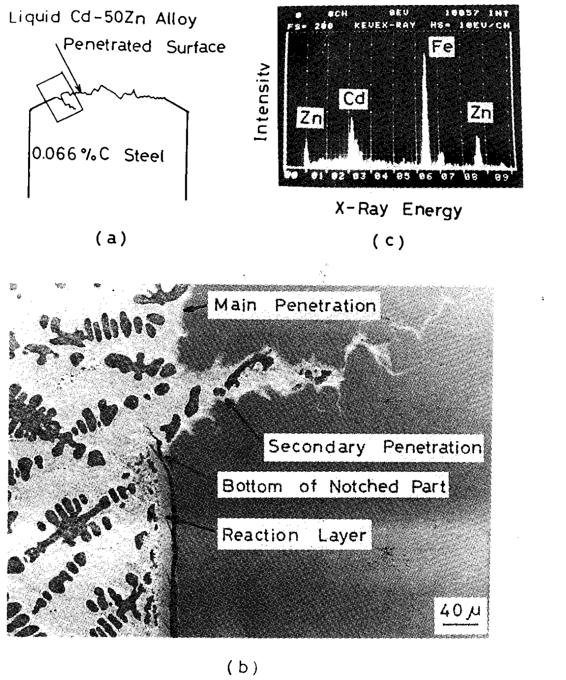

Fig. 7 LME of 0.066%C steel in contact with liquid Cd-50Zn alloy at 450°C. (a) Schematic view of LME ; (b) SEM photograph shown by inset on (a) ; (c) EDX result shown by reaction layer in (b).

may be expressed as follow:

$$k = Ae^{-Q/RT} \tag{2}$$

where k = rate, Q = activation energy for grain boundary penetration or erosion, A = frequency constant, R = universal gas constant and T = absolute temperature.

In the next section, we compare the mean penetration rate obtained in this study with the erosion constant of iron in liquid zinc.

3.4 Relation between mean penetration rate of LME and erosion of steel in liquid metal

Mean penetration rates of liquid Cd-50Zn alloy obtained from Figs. 4 and 6 are shown in **Figs. 8 and 9.** From Fig. 8, it is shown that the mean penetration rate decreases with rising temperature in both ranges below 480°C and above 520°C. However, as shown in Fig. 9, the mean penetration rate shows a maximum value at 500°C, in a temperature range of 480°C to 520°C.

Figs. 10 and 11 show the results obtained by Horstman and Peters[3)] of erosion of iron in liquid zinc which is controlled by palabolic time-rule, whereas Fig. 11 shows that it is controlled in the temperature range of 480 to 520°C by linear time-rule. Thus, it is observed that both phenomena have notably similar tendency. From eq. (2) and Fig. 8, these values of the apparent activation energy (Q_P) for the penetration are 3.6 kcal/mol below 480°C

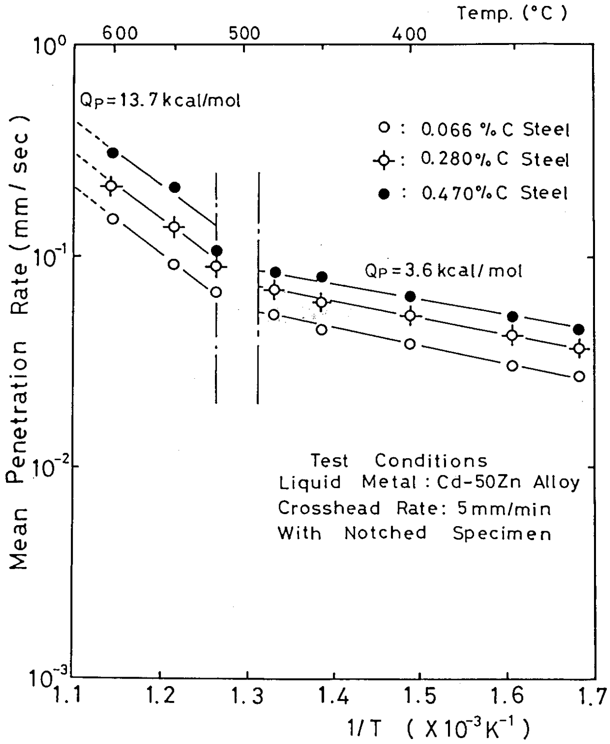

Fig. 8 Semilogarithmic plot of mean penetration rate as function of reciprocal absolute temperature

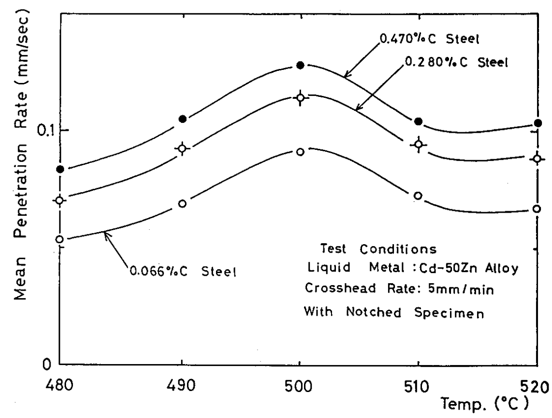

Fig. 9 Relation between temperature and mean penetration rate

and 13.7 kcal/mol above 520°C, respectively. The values of the activation energy (Q_e) for the erosion are 14.5 kcal/mol in the temperature range below 480°C and 41.2 kcal/mol above 520°C, respectively. Thus, the values of the apparent activation energy for the penetration are lowered to a third or a quater of these for erosion. The authors considered that the difference of the activation energy for both phenomena may be due to the existence of Cd in liquid Zn and the penetration of liquid alloy along the grain boundary.

The comparison of the mean penetration rate with the erosion constant in the temperature range of 480°C to 520°C are made from Figs. 9 and 11. From these results, it is shown that the LME behavior of carbon steels in liquid Cd-50Zn alloy is similar to that of erosion of iron in liquid

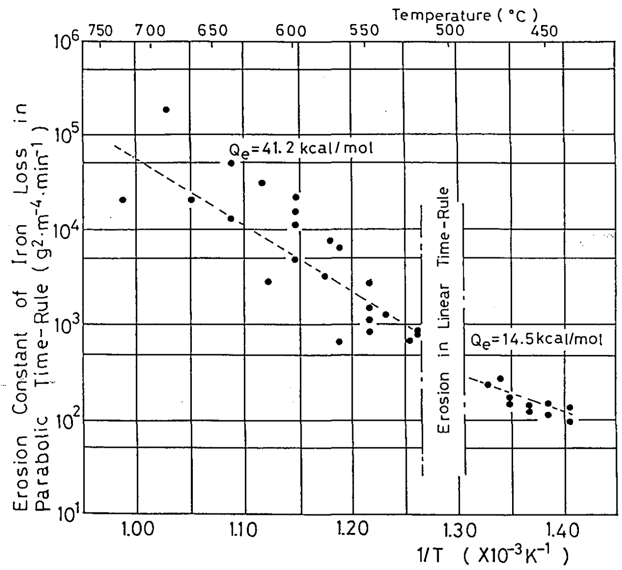

Fig. 10 Temperature dependence of erosion constant in parabolic regions[3)]

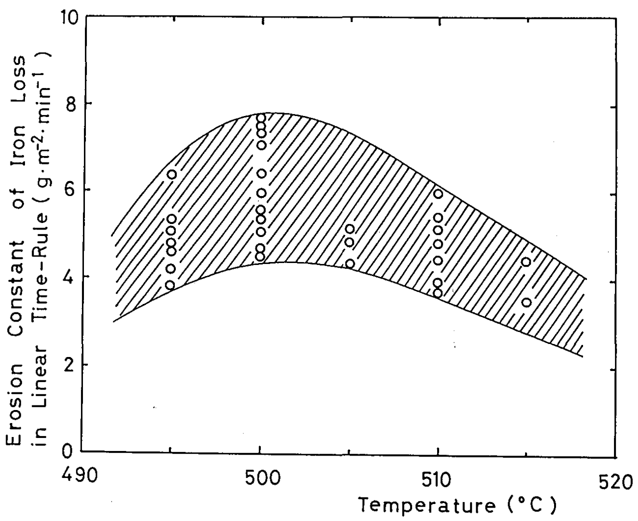

Fig. 11 Temperature dependence of erosion constant in linear region[3)]

metal under the changes in temperature. Moreover, Horstmann[4)] reported that erosion of iron was increased with increase in carbon content of steel. This tendency is also similar to the result that the susceptibility of LME increases with increase of carbon content in steels in this study. Thus, it is considered that the erosion of iron in zinc plays an important role in the grain boundary penetration of LME with Cd-Zn alloy.

4. Conclusions

The effect of temperature on LME was studied for carbon steels/liquid Cd-Zn alloys couples, using an Instron-type testing machine under the constant crosshead speed. From the results of tensile test, the susceptibility of carbon steel in liquid metal environment was evaluated by the time to maximum load and the mean penetration length at fracture. Moreover, the authors discussed relation between the erosion of iron in liquid zinc and the mean penetration rate.

The results obtained are as follows:

1) Various carbon steels in contact with a liquid Cd-50Zn alloy are severly embrittled with increases in both temperature and carbon content in steels. However, for a liquid Cd-5Zn alloy, the sensitivity of LME lowers with increasing temperature above 450°C.
2) Comparing LME phenomena with temperature dependence of erosion of iron in liquid zinc, it may be concluded that the erosion of carbon steel in a liquid Cd-Zn alloy is an important factor dominating the LME of carbon steel.

Acknowledgments

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