Environmental and material influences on liquid metal attacks targeting aluminum alloys

Judah Finley

Mentored by Dr. Collins and Mr. Debow

Introduction

Liquid metals have been known to cause catastrophic structural failure when applied to solid metals. "Liquid metal attack" (LMA) is especially significant when gallium contacts aluminum alloys. An LMA is the combined effect of a liquid metal penetrating into a solid metal (Senel et al., 2014), embrittling the solid metal, thus reducing the yield strength of the solid metal (Ina & Koizumi, 2004), and accelerating the corrosion of the solid metal (Mizusawa & Sakurai, 2009). Previous research indicates that environmental factors, such as temperature, humidity, static load, and exposure time as well as material factors, like the aluminum alloy, gallium alloy, and bar cross section impact the effects of an LMA. The purpose of this project is to determine the effect of environmental and material factors on structural degradation of aluminum bars caused by liquid metal gallium alloys. This knowledge could prevent damage caused by liquid metals.

Materials and Methods

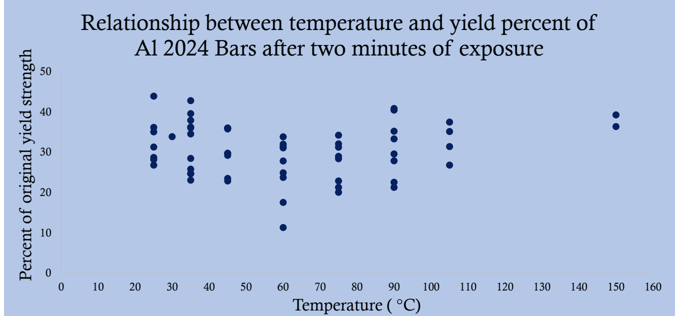
The study consisted of three experimental categories: temperature, humidity, and static load. In each, a bar and liquid metal were selected, and the material properties were recorded. Aluminum alloys included: 1100 (H14), 2024 (T351), 6061 (T651), 5052 (H36), and 7075 (T6) (cross sections ranging from 0.125 to 1.5 in.^{2}) and liquid metal alloys "46L," "GaSn," and pure Ga. A drop of liquid metal was applied and was allowed to penetrate for between 2 min and 30 min. A 3-point bend test was performed on each bar by the universal testing machine (UTM) (Fig. 1). The experimental temperature environment ranged from ambient to 250 °C. The humidity-controlled environment bars were tested between 16% and 89% relative humidity and monitored by a GoPro8. In the static-load experiment, bars were put under a load between 100 pounds and 1000 pounds until failure (when the bar deformed dramatically).

Figure 1 (left): Aluminum bar loaded into the UTM. The outer points are four inches apart. The fulcrum moves upward creating a constant displacement for the 3-point bend. The UTM measures the load and displacement applied to the bar. Material properties such as yield strength and Young modulus of the bar can then be calculated.

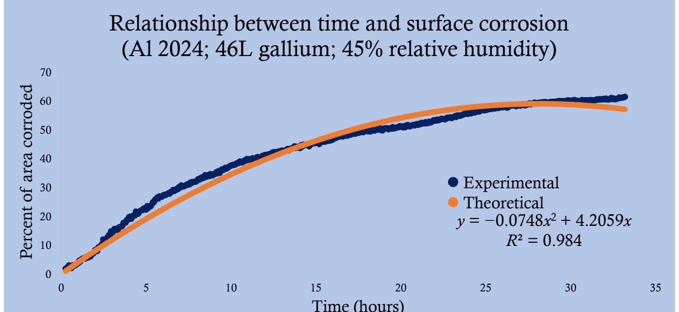
Results

LMAs appear to be most effective at 60 °C (Graph 1). All gallium alloys tested became solid below 10 °C and thus do not cause LMA. Tests below 10 °C are not shown in Graph 1. The yield strength of the bar decreased as the temperature increased until around 60 °C. At that point, the yield strength began to rise to a similar level as the 25 °C tests, plateauing around 105 °C.

At lower humidities no combination of aluminum and gallium alloys corroded. As the humidity increased the corrosion rate increased (Graph 2). Bars 2024 and 6061 corroded at similar rates, however 2024 bars shed larger flakes of aluminum oxide (Fig. 2). GaSn caused lesser corrosion rates than 46L. Untreated baseline bars did not corrode during the time of recording.



Graph 1 (below): The variation in the reduction of the original yield strength of the bar was 20% on average for each temperature tested. Identical bars occasionally failed at noticeably different load which may account for some of the error.



Graph 2 (above): The visible surface corrosion increased with time. The corrosion rate was inversely proportional to the surface area that the gallium penetrated over time. This aligns with the theoretical rate predicted by Fickian diffusion.

Results (cont.)

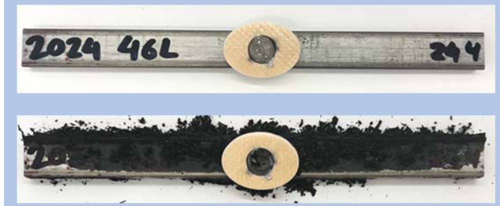


Figure 2 (left): Corrosion of a six-inch Al 2024 bar exposed to 46L at 45% relative humidity for 5 hours (above) and the same bar after 30 hours (below).

Bars held at lower static loads required more time to fail. Longer periods of static load testing resulted in greater observed ductility in the aluminum.

Discussion

The embrittlement effects of LMA were shown to be influenced by temperature, with around a 20% variance in failure load reduction across the 20 °C to 160 °C range tested. Note that increased temperature did not negate embrittlement effects—failure load reductions of 50% to 80% of the baseline yield strengths were observed at all experimental temperatures. The variance in results at any one temperature is likely derived from differences in the bar grain orientation. Determining grain orientation for each bar was beyond the scope of this study.

The humidity results indicate that if the humidity is kept below a certain level for the given solid/liquid metal system, the accelerated corrosion associated with liquid metal attacks can be prevented. This could prove significant for the possible use of liquid metal cooling systems in computer applications. These results suggest that computer designers might need to consider maintenance of a low humidity to mitigate potential liquid metal induced corrosion. Future studies could investigate differing humidity further.

References

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