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**HIGH TEMPERATURE ANALYSIS OF ALUMINUM-LITHIUM 2195 ALLOY
TO AID IN THE DESIGN OF IMPROVED WELDING TECHNIQUES**

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Introduction

Aluminum-lithium alloys have extraordinary properties. The addition of lithium to an aluminum alloy decreases its density, while making large increases in its strength and hardness. The down side is that they are unstable at higher temperatures, and are subsequently difficult to weld or even manufacture. Martin Marietta, though, developed an aluminum-lithium alloy 2195 that was reported to have exceptional properties and good weld-ability. Thus, it was chosen as the alloy for the space shuttles super light external tank.

Unfortunately, welding 2195 has turned out to be much more of a challenge than anticipated. Thus, research has been undergone in order to understand the mechanisms that are causing the welding problems. Gas reactions have been observed to be detrimental to weld strength. Water vapor has often been identified as having a significant role in these reactions [1] [2]. Nitrogen, however, has also been shown to have a direct correlation to porosity [3] [4]. These reactions were suspected as being complex and responsible for the two main problems of welding 2195. One, the initial welds of 2195 are much weaker than the parent metal. Second, each subsequent welding pass increases the size and number of cracks and porosity, yielding significant reductions in strength.

Consequently, the objective of this research was to characterize the high-temperature reactions of 2195 in order to understand the mechanisms for crack growth and the formation of porosity in welds. In order to accomplish that goal, an optical hot-stage microscope, HSM, was used to observe those reactions as they occurred. Surface reactions of 2195 were observed in a variety of environments, such as air, vacuum, nitrogen and helium. For comparison, some samples of Al - 2219 were also observed. Some of the reacted surfaces were then analyzed on a scanning electron microscope, SEM. Additionally, a gas chromatograph was used to analyze the gaseous products of the high temperature reactions.

Procedure

The samples observed in the HSM were machined into a bullet-like shape, reference Figure 1, ($d = 7\text{mm}$, $h = 12\text{mm}$). The bottoms of the samples were then polished and etched. The inverted microscope had a stainless steel vacuum chamber with a quartz window in the bottom. The electric heater used two tungsten heating elements to nearly completely surround the sides of the sample. The temperature was measured using a K-type thermocouple. It was inserted into a small hole in the side of the sample. The environments used were helium, air, nitrogen, and vacuum. Pressures varied from 1 bar down to 1.0×10^{-7} bars. Each sample was video taped and temperature measurements were recorded at regular intervals and at the initiation of reactions.

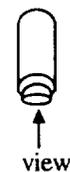


Figure 1: HSM sample

In order to aid the optical observations on the HSM, some of the samples were analyzed on an SEM. The reacted surface of the samples were examined for porosity, cracks, and anything unusual. High definition photographs and composition analyses were taken of the most important features.

An apparatus was constructed to analyze the gaseous products of the high temperature reactions of 2195 with a gas chromatograph. A long alumina tube was connected to a flexible hose and valve via a short piece of rubber tubing. A piece of 2195 was inserted into the tube. The tube was completely evacuated and filled to 1 psia with either room air or 99.999% N₂. The apparatus was then connected to the gas chromatograph. A small "clam shell" type ceramic heater (@ 620 °C) heated the bottom portion of the alumina tube for 15 minutes. At the end of this time, the sample was immediately analyzed by the gas chromatograph.

Results and Observations

Some dramatic and surprising results were observed in the hot-stage optical microscope, especially by comparison with 2219, bubbling, inhomogeneity, effects of degassing and worms. The most startling was bubbling through a liquid surface layer. The thickness of the liquid changed with various parameter changes. Bubbling was seen to occur at temperatures as low as 350 °C in weld metal and 530 °C in the parent metal. The bubbling usually started at the grain boundaries, cracks, pores, and second phases. Then later the reaction spread until the whole surface was reacting. The reactions often produced porosity throughout the metal. The reactions were self-sustaining. Once the reaction had begun to take place, even if the power to the heater was reduced or cut off completely, the reaction would continue and the temperature remain elevated.

Inhomogeneity was also observed in the 2195 samples. Both melting temperatures and reaction temperatures were observed to differ by as much as 40 °C within the same viewing area of a single sample. Inhomogeneity was seen coupled with the supposed presence of impurities when a small section of a sample was seen to react internally, melting at 350 °C. The section then quickly re-crystallized as the heat from the reaction was dissipated into the rest of the sample. The whole region later began to melt and react at 534 °C.

Violent surface reactions were observable in any atmosphere if the sample was not degassed. If the sample was degassed, the reactions in a nitrogen environment were reduced and the liquid layer was thinner, but bubbling still occurred. If the samples were not degassed and were heated at atmospheric pressure in any gas environment, worms were seen growing out of the parent metal at 400 °C. The reacted surface of the samples were also covered with a white, water soluble substance, probably LiOH. Satisfactory degassing was accomplished by vacuum baking the samples at 1.0×10^{-7} bars and 300 - 400 °C for 1-2 hours in the HSM. Degassing didn't have much effect when samples were heated in air, above 1×10^{-4} bars.

The scanning electron microscope also gave important results. The reacted surface of several of the samples tested revealed that large amounts of Nitrogen and Oxygen, generally around 70%, were present at the surface. Unfortunately, lithium and hydrogen are not detectable by an SEM, so complete analyses were not possible. Craters and pores were observed on the surface of reacted samples, reference Figure 3. Also, one should note that the pores or craters were created in the parent metal, so these are not merely pre-existing pores from a poor weld that migrated to the surface. Polished cross sections of the reacted samples show that porosity and cracks can be formed in the parent metal by exposure to air or nitrogen at high temperatures.

The gas chromatograph provided excellent results. This experiment proved that hydrogen is indeed bubbling from the surface of 2195. When the tube was initially filled with air, the reacted sample released hydrogen, nitrogen was consumed, and the oxygen level remained basically the same. In an atmosphere of pure nitrogen, 1 mole of hydrogen was produced for every 1.1 moles of nitrogen consumed. There aren't any 1:1 molar reactions possible with these reactants, nitrogen is always consumed much slower than hydrogen is released. But, because the H₂ that is produced will react with Li⁺ forming LiH, it is conjectured that lots of hydrogen is produced, but only one mole actually escapes for every mole of nitrogen consumed.

Chemical Reactions

An important step to solving the welding problem is to characterize the actual chemical reactions that are taking place. Some thought and research has already been put into this, however, it is difficult because there are a number of reactions that are occurring simultaneously. The main mechanism for the creation of porosity in 2195 is the reaction of lithium with water vapor and nitrogen, but it is the release of hydrogen that actually forms the pores. The reactions begin with H₂O that is adsorbed and bonded onto the surface of the metal. It is bonded to hydroxides, oxyhydroxides, and hydrous oxides, like aluminum oxide, Al₂O₃ * 3H₂O and some other compounds like LiNO₃* 3H₂O. [1] The reaction of Li with H₂O produces LiOH and evolves H₂. The fact that bubbling is seen in a Helium environment if the sample is not degassed, supports that. If both nitrogen and water vapor are available, then the following reactions are believed to be in effect:



The liquid layer observed on the surface of the metal during reaction is thought to be mainly a melted mixture of those compounds. Such a homogeneous mixture would have some median melting point, perhaps around 530 - 570 °C, which is the temperature range at which the surface is observed to be liquid and begin bubbling. Lithium will also react with aluminum oxide to form AlLiO₂, a much more porous oxide. There are also many other compounds that can be present formed from reactions of aluminum and magnesium. Clearly this is a complicated process.

Some Implications For Welding

Many studies have been done by the Soviets to demonstrate that there is a large amount of water vapor adsorbed into the surface of 2195 that causes porosity when welding. They showed that the removal of 0.2 - 0.3 mm of material from the surface is essential. They were able to eliminate porosity and generate welds of 82% of the base metal properties. [1] Studies in the U.S. have shown that hydrogen has the highest concentration 0.2 mm from the surface, reference Figure 2, supporting the

Russian results. [2] The Russians also demonstrated that water vapor can be re-absorbed into the surface of the metal at room temperature. Weld porosity was observed with materials chemically milled 16 days prior to welding. Which leads to an important word of caution for welding: Although the metal may be free from discoloring oxides, it can still be totally re-saturated with water vapor.

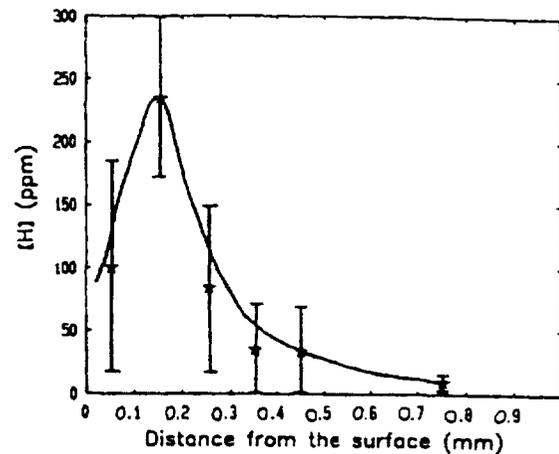


Figure 2: Hydrogen Distribution in Al-Li Alloy

Another fact that came out of this research is that previously welded 2195 is susceptible to violent surface reactions if exposed to air while at temperatures as low as 350 °C. Also, worms of material were seen growing out of the parent metal at 400 °C, yet to the naked eye the surface appeared unreacted. That underscores the importance of shielding the weld for a length of time that allows the metal to cool below those temperatures, as well as the necessity to back shield for cover passes and repair welds.

Conclusions

In conclusion, weld zone cracks and porosity arise principally out of a reactions of lithium with nitrogen and water vapor adsorbed or bonded to the surface of the metal, which releases a large amount of hydrogen into the weld pool. Thus, this research has led to two important applications for welding:

- One, the time lapse after surface preparation of Al-Li 2195 is extremely important. Milling the surface must be performed immediately prior to welding because water can be re-adsorbed from humid air, over time.
- Two, Al-Li 2195 needs to be shielded when it is at temperatures above 350 °C. Back shielding is a necessity, even for partial penetration cover passes. Pending temperature profile studies behind the weld, a trailing shield should be considered.

Work still needs to be done to attempt to further understand the way in which porosity and crack growth are propagated in this material. Work, too, should be performed to analyze how quickly Al-Li 2195 adsorbs water. Lastly, work should be done directly in the shop environment, in order to devise ways of improving current shop practices, based on an understanding of the reactivity and sensitivity of this alloy.

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References

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Figure 3: Reacted surface of Parent Al-Li 2195 (Room Air, Pressure = 4×10^{-4} bars)