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LIQUID OXYGEN (LOX) COMPATIBILITY EVALUATIONS OF ALUMINUM LITHIUM (Al-Li) ALLOYS : INVESTIGATION OF THE ALCOA 2090 AND MMC WELDALITE 049 ALLOYS

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LIQUID OXYGEN LOX COMPATIBILITY EVALUATIONS OF ALUMINUM LITHIUM (Al-Li) ALLOYS : INVESTIGATION OF THE ALCOA 2090 AND MMC WELDALITE 049 ALLOYS

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ABSTRACT

The present research work is an investigation into the behavior of liquid oxygen LOX compatibility of aluminum lithium (Al-Li) alloys. Alloy systems of Alcoa 2090, vintages 1-3, and of Martin Marietta Corporation MMC Weldalite 049 were evaluated for their behavior related to the LOX compatibility employing liquid oxygen impact test conditions under ambient pressures and upto 1000 psi. The developments of these aluminum lithium alloys are of critical and significant interest because of their lower densities and higher specific strengths and improved mechanical properties at cryogenic temperatures. Of the different LOX impact tests carried out at the Marshall Space Flight Center (MSFC) , it is seen that in certain test conditions at higher pressures , not all Al-Li alloys are LOX compatible. In case of any reactivity, it appears that lithium makes the material more sensitive at grain boundaries due to microstructural inhomogeneities and associated precipitate free zones (PFZ). The objectives of this research were to identify and rationalize the microstructural mechanisms that could be related to LOX compatibility behavior of the alloy system in consideration.

The LOX compatibility behavior of Al-Li 2090 and Weldalite 049 is analyzed in detail using microstructural characterization techniques with light optical metallography, Scanning Electron Micropscopy (SEM) , electron microprobe analysis , and surface studies using Secondary Ion Mass Spectrometry (SIMS), Electron Spectroscopy in Chemical Analysis (ESCA) and Auger Electron spectroscopy (AES). Differences in the behavior of these aluminum lithium alloys are assesed and related to their chemistry , heat treatment conditions and microstructural effects.

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I. INTRODUCTION

The developments of the new aluminum lithium Al-Li alloys have been driven due to high performance demands of aerospace applications and for use of materials in Space Transportation Systems and as cryotankage materials. Lithium is the lightest element and the only metal, with the exception of beryllium that is toxic , expensive and difficult to use , which alloyed with aluminum is known to improve both the modulus and the density of these Al-Li alloys in place of current conventional alloys. This can reduce the weight by 7-15 % and increase the elastic modulus by 10-20 %. For these and several other special advantages, the aluminum lithium alloys are now gaining considerable importance as the future advanced aerospace materials.(1,2). Understanding the behavior of these materials is of special interest to MSFC and of particular interest is the cryogenic behavior and the LOX compatibility behavior of these materials as this could advance and affect the applications of these aluminum lithium alloys as the future advanced cryogenic materials.

Design and developmental aspects of certain Al-Li based alloys (3-11), their fundamental characteristics, special advantages at cryogenic temperatures, superior fracture toughness at ambient and cryogenic temperatures, and the corrosion and weldability of these high strength Al-Li alloys (12-16) have all shown immense potentials of these developing aluminum lithium based alloys. For these potentials to be realized, further in-depth scientific and technological, commercial evaluations of these alloy systems are essential and vital to the future development of these alloy systems.

The cryogenic behavior of the Al-Li 2090 has exhibited improved fracture toughness between room temperature 298K and liquid helium 4K temperatures (12-14). This improved strength toughness relationship is similar to the earlier data of J. Glazer et. al. (12) on standard aerospace and 2219 aluminum alloys. However, the origin of this behavior is not clear and further such behavior has not been shown in the short transverse orientations and has not been found for all alloys and aging conditions. There is clearly need to evaluate the cryogenic mechanical behavior of the developing Al-Li alloys and to understand the mechanisms responsible for such behavior and relationships between the microstructures and potential cryogenic properties. A good description and understanding of the microstructures and development of microconstituents is essential to the understanding of such structure property relationships.

Of the many potential applications for the Al-Li alloys, the most prominent are as cryotankage materials and for LOX environments. In recent LOX impact compatibility tests at MSFC, it is seen that not all Al-Li alloys of different chemistry and specifications are compatible under some test conditions at higher pressures. The reasons for these LOX sensitivity and the mechanisms related to the LOX compatibility are not currently understood and this research has been undertaken to identify the causes of such reduced LOX compatibility and sensitivity of certain specimens of Al-Li alloys and their related microstructural mechanisms. This investigation has centered on the evaluations of material supplied by Alcoa of Al-Li 2090,T8E41, vintages 1-3, and of Weldalite 049 alloys T4 and T8 tempers supplied by the Martin Marietta Corporation.

Of the LOX impact tests ,as per NHB 8060.1B (17), using the Army Ballistic Missile Agency ABMA type tester,in the tests carried out it has been observed that Weldalite 049 is mostly seen as compatible but more tests are required. The Alcoa 2090 exhibited improvements from vintage 1 to vintage 3. No reaction was observed in the vintage 3 materials. The mechanisms of the LOX compatibility and sensitivity were analyzed using metallographic techniques, x-ray diffraction, SEM and microprobe studies, and surface studies using ESCA, SIMS and Auger spectroscopy and related to microstructural characterizations, chemistry and processing conditions of the specific Al-Li alloys.

II. OBJECTIVES

The objectives of this research that has been pursued are:

- O Evaluation of LOX Compatibility Impact Test procedures , testing , and data analysis
- O Characterization of the microstructures of the aged and unaged 2090 and Weldalite 049 in suitable tempers in sheet and / or plate form of the typical "as received", "reacted" and "unreacted" LOX tested material specimens
- O Analyses of LOX test results, their predicted behavior, relationships with material chemistry and tempers, and microstructural characterization
- O Correlation of material properties with microstructure and test results
- O Development of rationale for LOX Compatibility criteria and material behavior

III. EXPERIMENTAL PROCEDURES

The starting materials comprised of aluminum lithium alloys 2090-T8E41, in vintages 1-3, supplied by Alcoa and from Weldalite 049 alloys of T4 and T8 tempers supplied by Martin Marietta Corporation and also of conventional aluminum copper Alcoa 2219 materials. These several formulations and tempers were produced by appropriate solution heat treatment, quenching, cold work and aging for suitable time and temperature conditions. Details of the tested 2090, Weldalite 049 and 2219 alloy chemistry, heat treatment and temper conditions are provided in Table 1. All test materials were produced as 11/16-in. diameter discs, .063-in. / or .125 in. thick, and tested as per NHB 8060.1B using the Army Ballistic Missile Agency ABMA type impact tester. The test method is similar to standard ASTM D 2512.82 for compatibility of materials with liquid oxygen (18). All of the necessary and special precautions as in the test specifications are strictly adhered to in carrying out the LOX impact compatibility tests. This includes special degreasing, cleaning, drying and packing of the test specimens before carrying out of the actual LOX impact tests.

In accordance with NHB 8060.1B, a material is considered to have material sensitivity if at shows any reaction in 20 successive impact tests at 10 kg-m (72 ft.-lbs) . A material is said to show sensitivity or reaction if the test results in any of the conditions such as : audible explosion, flash, evidence of burning or charring, or major discoloration. These test criteria are used to evaluate the performance of all test materials. In order to assess the behavior of the 2090 and Weldalite 049 , selected test specimens of the typical as received , reacted and unreacted specimens of these alloy systems were evaluated using standard metallographic procedures, x-ray diffraction, SEM, electron microprobe analysis, ESCA, SIMS and Auger spectroscopy in an effort to analyze the microconstituents and their behavior related to LOX impact compatibility of these particular Al-Li alloys.

Metallographic analyses for microconstituent characteristics , inhomogeneities, any precipitate free zones PFZ , deformation and heat treatment effects etc. were carried out using standard procedures and suitable etching techniques. The grain boundaries seem to have shown enhanced effects with use of the differential interference contrast DIC microscopy. Where possible, microhardness measurements were taken of certain Cu/Fe rich precipitates . In conjunction with metallographic analyses , some SEM and electron probe microanalysis work was performed. This revealed presence of Al in base material and some Cu/Fe rich particles as evidenced by SEM and microprobe analyses. These analyses ,however, were not capable to characterize and identify the presence of Li. The SEM scanning electron microscopy with energy dispersive analysis was carried out on Cambridge Stereoscan Model 250 Mark II, and microprobe work was carried on CAMICA SX model. The analyses of the presence of lithium and lithium related phases by the ESCA, SIMS and Auger spectroscopy techniques of reaction products of some of the test specimens were carried out. These , however, were useful to detect Li and to understand the behavior of these materials and nature of some of the reaction products.

The x-ray photo electron spectroscopy (XPS) or the electron spectroscopy in chemical analysis (ESCA) was performed on Surface Science Instrument the SSX - 100 ESCA spectrometer, and the Auger electron spectroscopy (AES) was performed using Modified Physical Electronics 545 Auger System. The secondary ion mass spectrometry (SIMS) was performed on a Modified UTI 100C 3M model. The results of these several analyses and related microstructural mechanisms that could be affecting the LOX compatibility behavior of the Al-Li alloys under investigation are presented in the next section.

Table 1A Compositions of AA 2090 and Weldalite 049

AA 2090

Li	Cu	Si	Fe	Mn	Mg	Cr	Zn
1.9-2.6	2.4-3.0	.10	.12	.05	<.25	.05	<.10

Zr	Ti	other (each)	other (tot.)	Al
.08-.15	<.15	<.05	<.15	bal.

Weldalite 049

Li	Cu	Ag	Mg	Zr	Al
1.3	6.0	0.4	0.4	0.14	bal.

AA 2219

Cu	Mn	Ti	Al
6.3	0.30	0.06	bal.

Table 1B Tempers and heat treatments

AA 2090	SHT 1000 - 1020 F , 2 - 6 % CW , aging 300 - 350 F for different times. (T8E41)
Weldalite 049	SHT 940 F , natural age > 600 hrs. (T4) SHT 940 F , 3 % CW , art. age 20 hrs. 160C(T8)
AA 2219	SHT 995 F ; art. age 350 F , 18 hrs. (T81)

IV. RESULTS AND DISCUSSION

The LOX impact compatibility test data are shown in Table 2A-C. These LOX impact compatibility evaluations were carried out by conducting tests under liquid oxygen under fixed pressure at ambient pressure and upto 1000 psi.

For assessment of the LOX cryogenic behavior of the Al-Li alloys, it is first essential to understand the precipitation mechanisms in these alloy systems, their phase equilibria information as related to strengthening mechanisms, and then evaluate and rationalize the several metallographic characterizations and results of the surface studies.

A. Precipitation Strengthening and Phase Equilibria in Al-Li based alloy systems

The phase equilibria diagrams of interest related to the Al-Li based alloy systems under study are presented in figures 1 and 2. As is well known , for an alloy system to be amenable to age hardening , there must be a decrease in solid solubility of one or more of the alloying elements with decreasing temperature. Major alloying elements of interest in the systems under investigation include Cu, Mg and Li. Some of the information on the phase transformations in this section is based on references 19-23.

Lithium produces order strengthening superlattice L1 2 type precipitates of metastable δ' (Al_3Li). Additionally, phases such as T_1 (Al_2CuLi) or T_2 (Al_5CuLi) are potential strengthening phases alongwith θ' (Al_2Cu). It is further seen that with additions of transition metals such as of chromium, manganese and zirconium with solubilities less than 1 atomic % , potential improvements in alloy properties are possible. With Zr additions , grain refining microconstituent precipitates of β'(Al_3Zr) are known to be present that control the grain structure and inhibit recrystallization in the alloy system.

The nature and formation of coherent particles of δ' by order strengthening mechanism, variations in distributions of this and associated particle phases, interactions of these with dislocations, subgrains, and grain boundaries and localized plastic strain , and presence of precipitate free zones PFZ will affect the microstructural developments and thereby affect the strengthening behavior of these Al-Li based alloys. With higher copper content and presence of Mg, S' (Al_2CuMg) precipitates can be formed.In analyzing the Al-Li 2090 and Weldalite 049 alloys, it is seen that only limited phase equilibria information is available related to these systems. These include investigations of Sigli and Sanchez (20) and of Flower and Gregson (21), (23). The additions of Ag and Mg give unique properties to these Al-Cu-Li alloys. For alloy design considerations, minor additions (~.4wt.%) of Ag and Mg are seen to stimulate precipitation and promote the refinement of strengthening phases. Pickens et. al. (8) and Langan and Pickens (9) have identified $\alpha_{ss} + T_1 + T_B$ phases for Al-Cu-Li alloy with 1.3 wt.% Li. The δ' (AL_3Li) phase is not considered to be present if T_B ($Al_{7.5}Cu_4Li$) phase is included on precipitation. These studies and identification of the multiple phases expected in Weldalite 049, particularly with variations in lithium , still need to be carried out in detail to confirm their nature and effects on the properties of these alloys.

The δ' particles are spherical and in some cases coprecipitate with β' (Al_3Zr) , and with T_1 phase precipitating as laths or platelets.Polmear and coworkers(24) have attributed the strengthening to increase in an Al-6.7Cu-0.5Mn alloy with 0.5 % Ag and 0.5 % Mg due to a Ω phase. This Ω phase precipitates with a plate like morphology and could be another potential strengthening phase in Weldalite 049. Studies related to this and T_1 phase are required to establish this and the morphology and composition of this Ω phase.

B. LOX Compatibility Evaluations and Metallographic Characterizations

The LOX impact compatibility test results of 2090, vintage 1, 100796 exhibited a rather violent reaction under 500 psi. LOX impact test conditions. This tested material was sectioned and examined for reaction products. This same vintage material had also shown at 100 psi. some holes in a reaction in which the impacter had melted together with bottom of the cup of inconel 718 material. This was also sectioned and examined for reaction products, figures 3A-c.

The Al-Li 2090 LOX tested specimens, in other cases , on reaction had only shown discoloration such as seen in figure 4. These reacted specimens were sectioned and examined for microstructural characteristics and potential causes for the LOX sensitivity and or reactivity of such materials.

The Weldalite 049, with 1.3 wt. % lithium , ~ 6 wt. % Cu and 0.4 % Ag, 0.4 % Mg additions, as received material shows on metallographic analysis effects of deformation , and presence of multiple phases as seen in figure 5. Plastic strain localization and unrecrystallized grain structure is clearly seen . This material of Weldalite T4 temper on LOX impact test conditions had shown no reaction. These alloys and also the Al-Li 2090 materials of several specimens , on etching with Graff / Sargent chemical etchant revealed presence of coarse particle preciptates , figure 6 and 7. These particles on detailed examination are identified as Cu/Fe rich precipitate particles. Wherever possible, these particles were tested for their microhardness. Hardness data of several Al-Li 2090 and Weldalite 049 specimens tested clearly exhibited that these particles had distinctly higher hardness than the matrix aluminum rich material , about 120 - 145 HV for matrix and 190-370 HV for the precipitate particles.

In case of Al-Li 2090 , vintage 1 , 100589, the as received material on microstructural examination shows typical pancake type microstructure with characteristic bead like or a necklace structure , with few precipitates only inside the interior of the grains. The localized precipitation at the grain boundaries , figure 8 , appears to produce the precipitate free zones PFZ areas. This causes lithium depletion and possibly is responsible for weakness and LOX impact sensitivity of these Al-Li materials. The localized behavior , and enhanced effect of the PFZ's can be better observed using differential interference contrast DIC microscopy. Effects of this and possible localized behavior at the grain boundaries are shown in figure 9. It is to be noted that the extent of the PFZ and the extent of the precipitate formation seems reduced from vintage 1 to vintage 3 material, as also is seen less LOX impact sensitivity in these materials. These effects could also be related to processing conditions, less inclusions, and trace elements such as Na,K,Ca,B etc. (25). The presence of possible PFZ's is very sparse and highly isolated when detected in case of Weldalite 049 alloys . It thus is indicative that the localized precipitation behavior , the PFZ, and ofcourse , the nature of the precipitating phases , all are contributing to the LOX impact compatibility of these Al-Li materials. With x-ray diffraction in some analyses,the aluminum rich matrix was indexed but other phases due to their small amounts could not be identified. As earlier discussed, the SEM analyses could not detect lithium and its related phases with any microprobe analyses, but identified the Cu/Fe rich precipitates in the materials that were examined.

TABLE 2A. ALUMINUM ALLOY IMPACT RESULTS - 2090 LOX IMPACT TEST

MATERIAL	14.7 psi	50 psi	100 psi	200 psi	500 psi	600 psi	1,000 psi
2090 - T8E41 0.063" thick 100496 Vintage 1	No Reactions 20 Impacts	2 Reactions 37 Impacts	5 Reactions 20 Impacts		1 Reaction 1 Impact Extremely Violent		1 Reaction 1 Impact Extremely Violent Reaction
2090 - T8E41 0.063" thick 100525 Vintage 1	No Reactions 20 Impacts	7 Reactions 20 Impacts					1 Reaction 3 Impacts Extremely Violent Reaction
2090 - T8E41 0.125" thick 100589 Vintage 1	No Reactions 20 Impacts	1 Reaction 60 Impacts	1 Reaction 33 Impacts	2 Reactions 45 Impacts	2 Reactions 12 Impacts		
2090 - T8E4 0.25 mach. to 0.125" 100797 Vintage 2		0 Reaction 100 Impacts			0 Reaction 25 Impacts		1 Reaction 20 Impacts
2090 - T83 0.125" thick 100796 Vintage 1			3 Reactions 20 Impacts 2 Reactions 20 Impacts		1 Reaction 1 Impact Very Violent		1 Reaction 1 Impact Very Violent
2090 - T8E41 0.125" thick 100796 Vintage 3		0 Reactions 100 Impacts					0 Reactions 20 Impacts

TABLE 2B. ALUMINUM ALLOY IMPACT RESULTS - WELDALITE LOX IMPACT TEST

MATERIAL	14.7 psi	50 psi	100 psi	200 psi	500 psi	600 psi	1,000 psi
Weldalite T4 0.125" thick 100524	No Reactions 20 Impacts	No Reactions 20 Impacts				No Reactions 20 Impacts	No Reactions 20 Impacts
Weldalite T8 0.125" thick 100781							0 Reactions 20 Impacts
Weldalite T8 0.125" thick 100781 Rerun 100910		No Reactions 100 Impacts					2 Reactions 18 Impacts Violent Reaction

TABLE 2C. ALUMINUM ALLOY IMPACT RESULTS - 2219 LOX IMPACT TEST

MATERIAL	14.7 psi	50 psi	100 psi	200 psi	500 psi	600 psi	1,000 psi
2219-T81 0.129" thich 100526	No Reactions 20 Impacts	No Reactions 20 Impacts				No Reactions 20 Impacts	No Reactions 20 Impacts
2219-T81 0.063" thick	No Reactions 20 Impacts	No Reactions 20 Impacts	No Reactions 20 Impacts		No Reactions 20 Impacts		No Reactions 20 Impacts

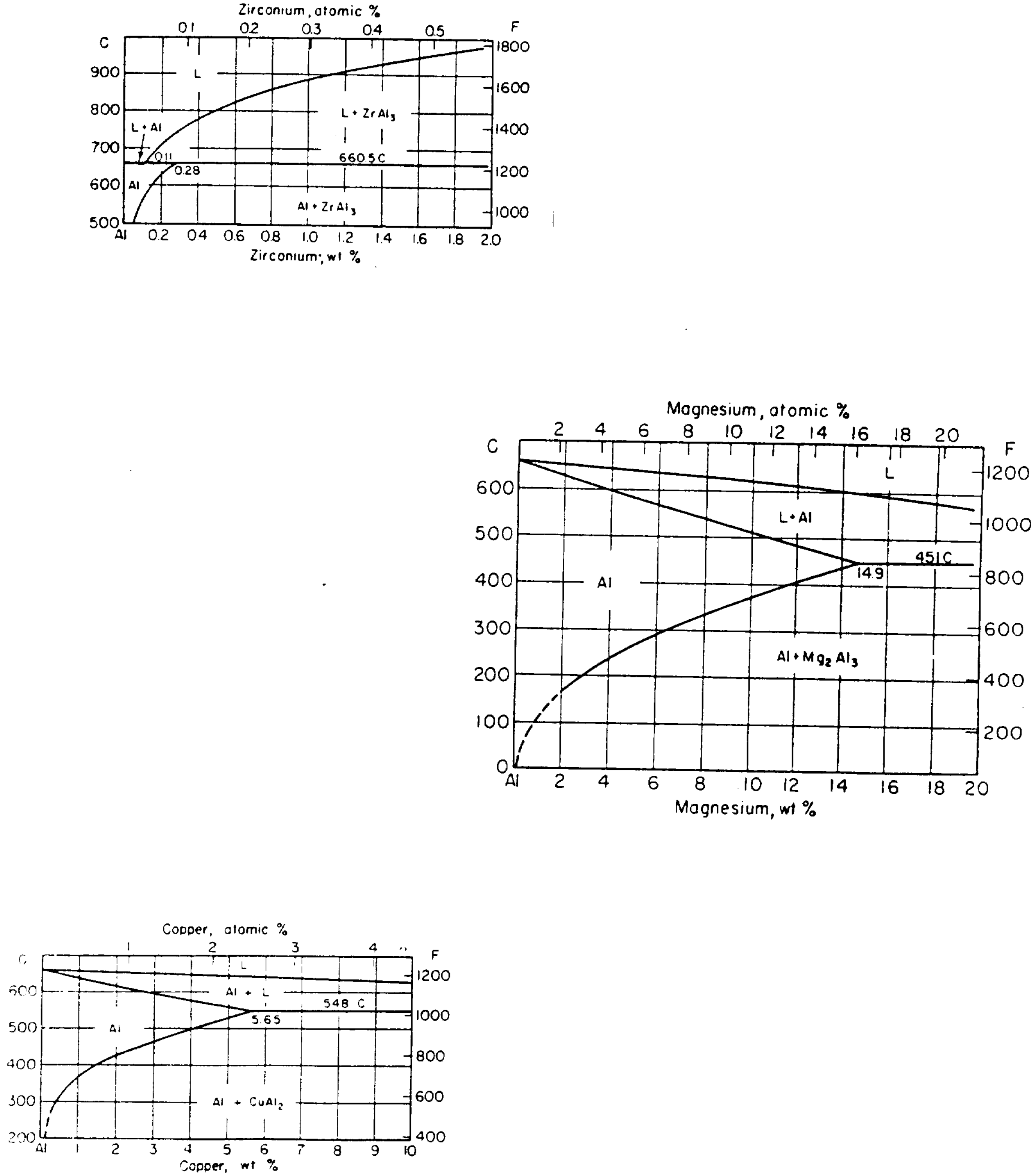


Fig.1 Section of Al-Zr, Al-Mg and Al-Cu phase diagrams showing limits of solid solubility (19).

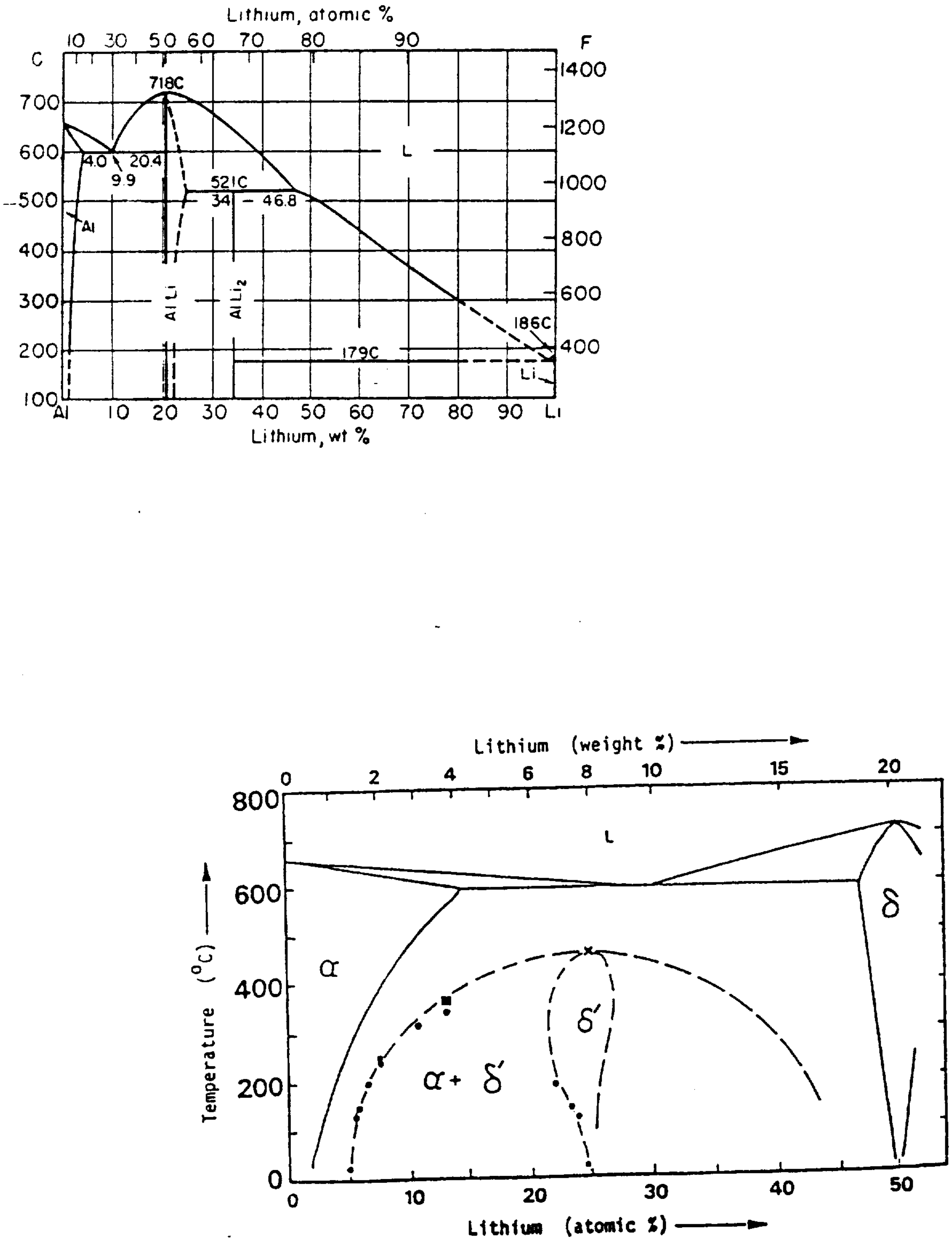
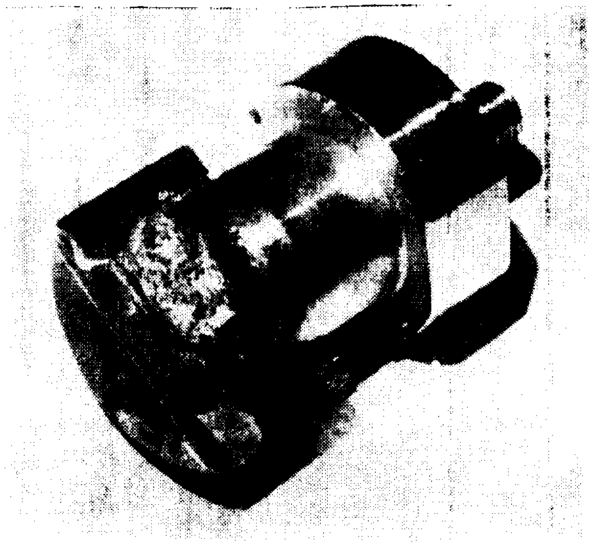
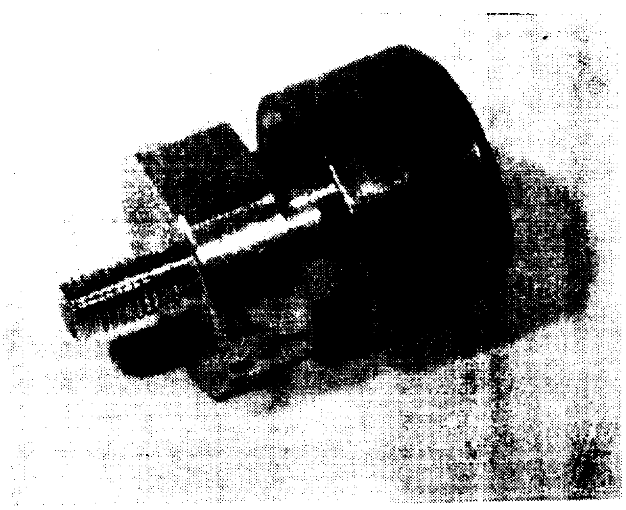


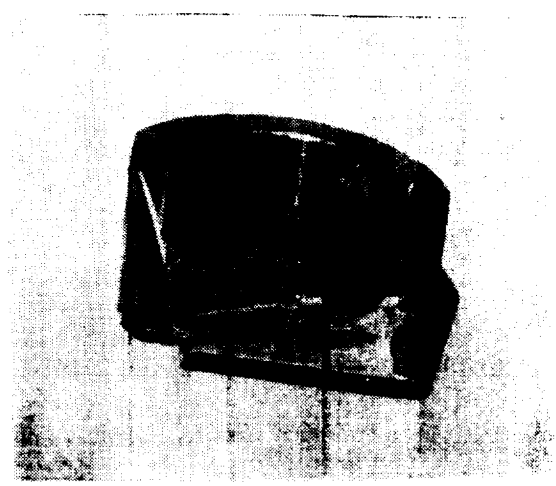
Fig.2 Al-Li phase diagram and section of the system showing presence of δ′(Al_3Li). (22).



(a)

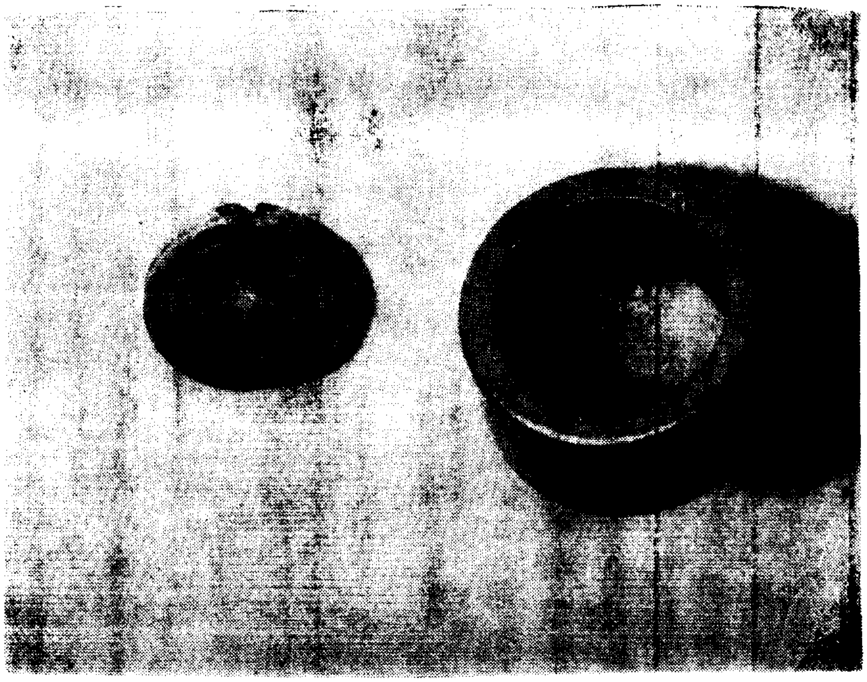
Fig. 3a Al-Li 2090-100796, vintage 1, LOX tested , 500 psi., cut-away section of the reacted specimen



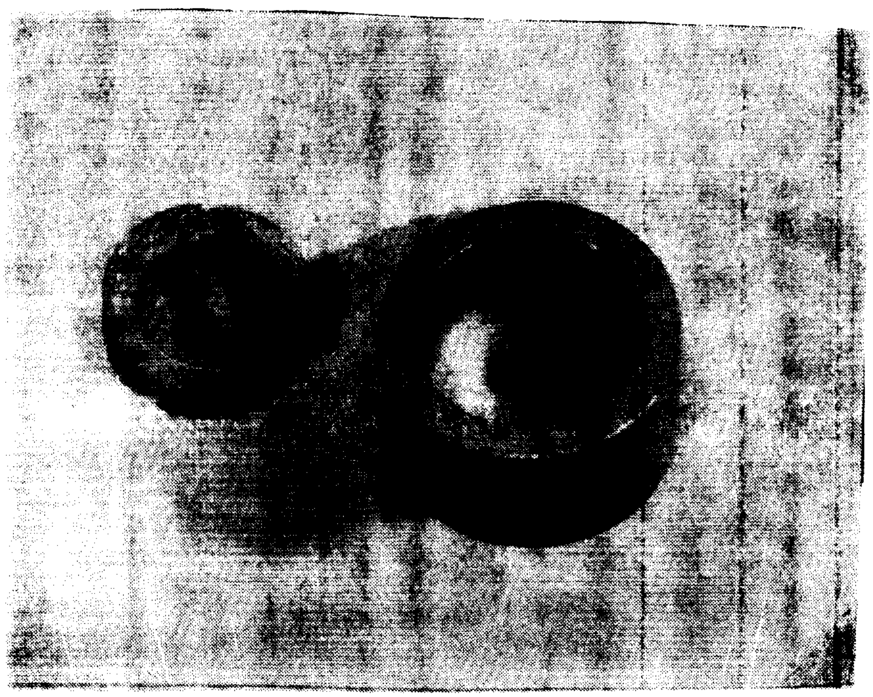


(b) (c)

Fig. 3b and 3c Al-Li 2090-100796, vintage 1, LOX tested 100 psi., As reacted (b), and cut-away of the same (c).



(a)



(b)

Fig.4 Al-Li 2090 LOX tested , at 100 psi. As reacted impact test specimen and test cup, (a)3/20 (b)2/20

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(a)

(b)

Fig.5 Al-Li Weldalite 049 As received (a) transverse section , 1000x (b) longitudinal section, 200x. This material shows no reaction on LOX testing.

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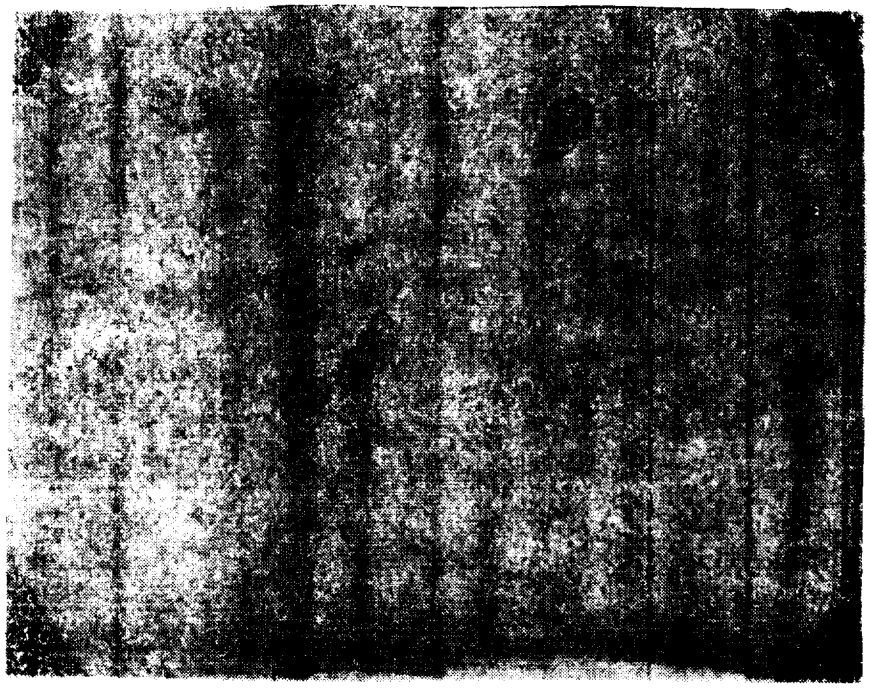
(a)

(b)

Fig.6 Al-Li Weldalite 049 (T4) As received
(a) longitudinal section Graff/Sargent 1000x
(b) transverse section Graff/Sargent 400x.



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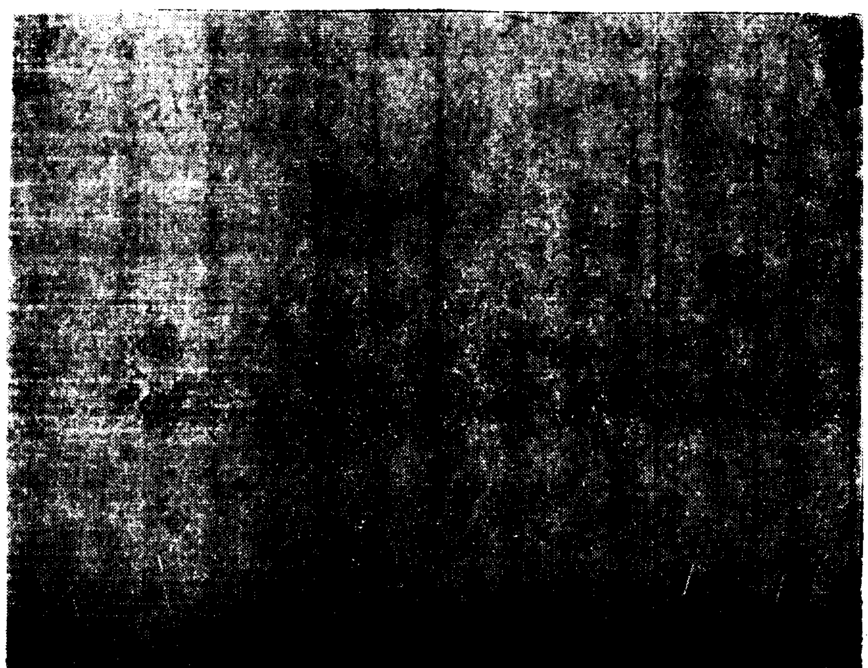

(b)

Fig.7 Al-Li 2090 - 100797 (a) LOX tested, 50 psi.
(b) LOX tested , 500 psi. ; Unreacted
Graff/Sargent, 1000x .

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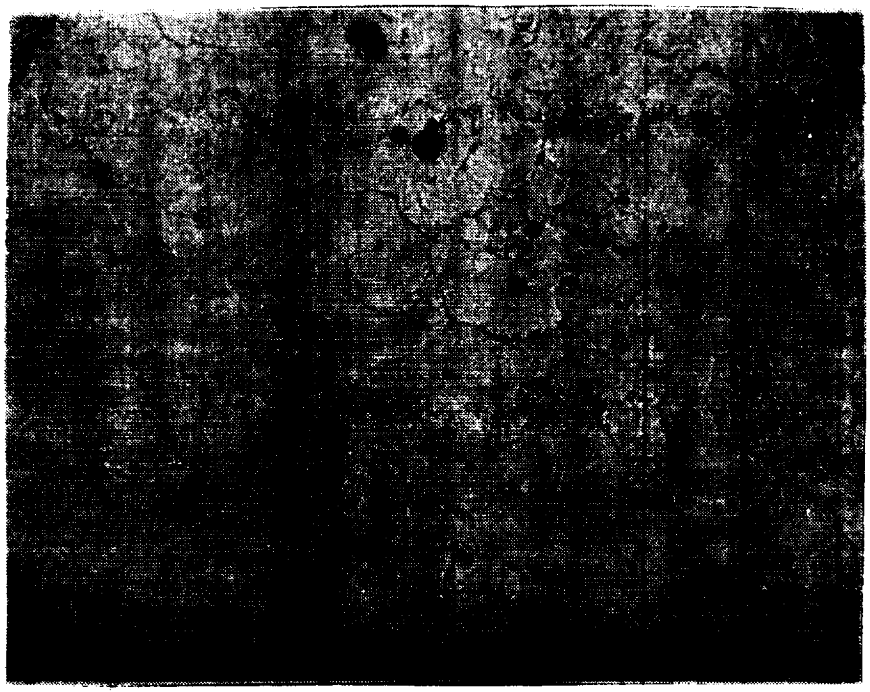
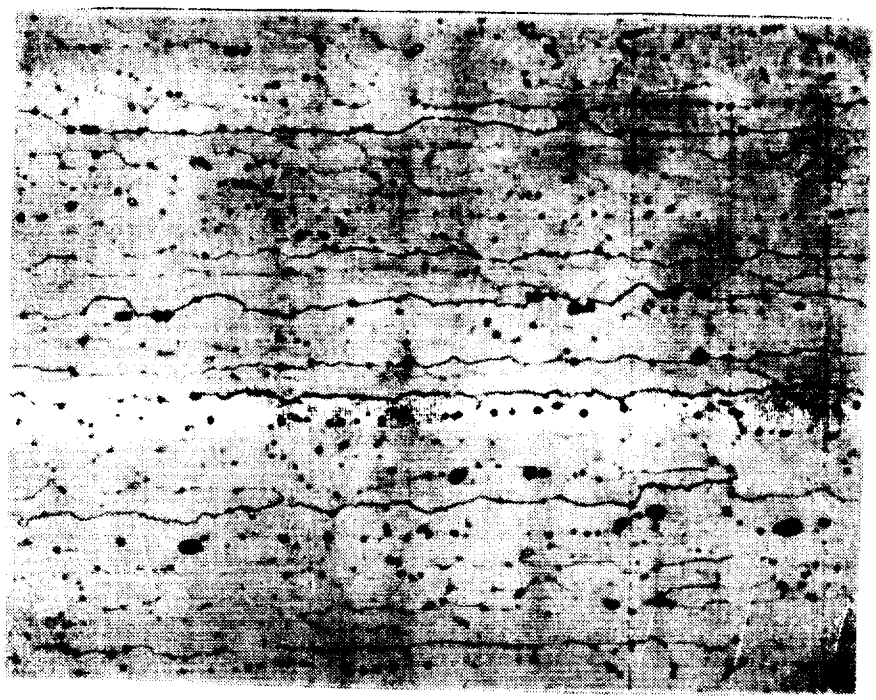


(a)



(b)

Fig.8 Al-Li 2090-100589 As Received (a) longitudinal section and (b) transverse section, 1000x .

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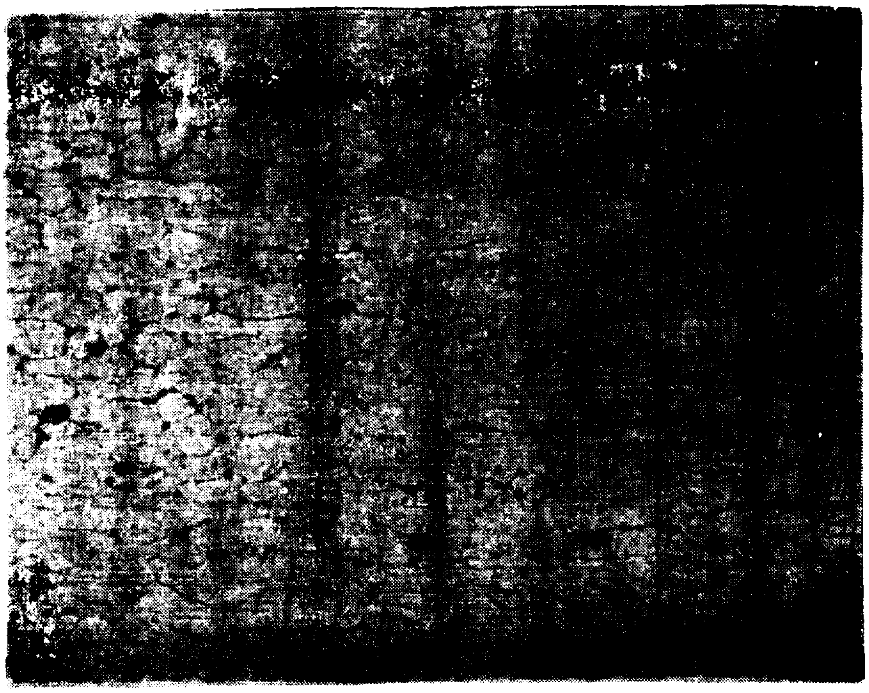
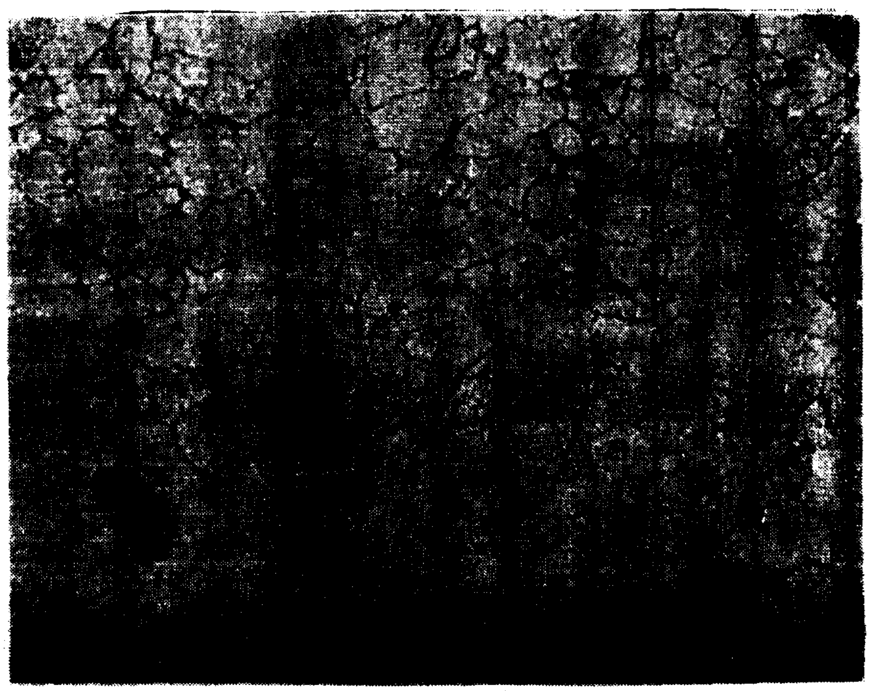


(a)



(b)

Fig.9 Al-Li 2090 LOX tested micrographs showing possible PFZ's and localized behavior at the grain boundaries (a) 2090-100796 , 100 psi. and (b) 2090-1000797 , 500 psi; unreacted .

C. Surface Studies and Analyses of the Reaction Products

XPS (ESCA), SIMS and Auger Spectroscopy (AES) techniques were used in analyses of reaction products after LOX impact testing in cases where severe reaction had caused the melting of not only of the test material but also of the test cup and the striker pin in the test assembly. In these , the test specimen , the inconel test cup and the test pin in examination of the section of the reacted specimen exhibited severe oxidation and gouging of inconel 718. In analyses of the grayish material of the reaction product, the characteristic peaks of these in ESCA related to mostly Al and O and small amounts of Cr. Al to O ratio in reaction product is found to be 0.64, close to that of Al/O ratio in Al_2O_3 . These analyses , also, could clearly detect the presence of Li, at 55 ev , and also appear close to peaks for LiO. In SIMS and Auger Spectroscopy, the dark gray material of the reaction product was analyzed . In these AES analyses, the surface charging was quite severe making useful signal analyses impossible. However, this in turn confirmed the material to be Al_2O_3 which is highly insulating in nature. SIMS and ESCA analyses confirm the presence of lithium and that the reaction product is Cr contaminated aluminum oxide. The identification of lithium and lithium related phases, for microanalyses and imaging of phases effectively causing the sensitivity could not be analyzed with SIMS equipment available at MSFC. A survey of related studies in the literature (26-29) for microanalysis of precipitates in aluminum lithium alloys indicates difficulties related to these analyses , and that these quantitative analyses possibly can be carried out with Scanning Ion Microprobe or with SIMS equipment with direct imaging capabilities for surface analyses of the bulk specimens or with Electron Loss Spectroscopy studies.

V. CONCLUSIONS AND RECOMMENDATIONS

Based on the LOX compatibility evaluations of the Al-Li 2090 and Weldalite 049 alloys and their relationships with the microstructural characterizations and the surface studies carried out in this study, the following conclusions can be made. Recommendations for further work are also made .

1. While Weldalite 049 is mostly seen as compatible in LOX impact tests, in Al-Li 2090 lithium makes this material more sensitive at grain boundaries in some cases due to PFZ's.

2. The Al-Li 2090 in LOX impact tests has shown improved behavior in vintage 2 material and has no reaction in vintage 3 ; the several factors related to this could be due to processing conditions and less inclusions, cleanliness , lower Na, K, etc.

3. The reactivity or the LOX compatibility behavior as related to microconstituents in case of Al-Li 2090 appears to be due to the strengthening phases such as δ' (Al_3Li) , θ' , and T_1 .

4. The strengthening behavior in these Al-Li alloys is mainly due to order hardening , and involves different particle sizes, shapes and distributions. In addition, there can be gross inhomogeneities such as PFZ's. The additional mechanisms of modulii strengthening and coherency strengthening to some extent also affect the strengthening behavior of these materials. The presence of Zr inhibits recrystallization in these materials and precipitates the β' phase.

5. The δ' phase is $L1_2$ ordered strengthening phase ; the coherency stregthening is not a very valid factor in strengthening as the misfit between the matrix and the δ' phase is very low about 0.1 %. In addition to the very fine strengthening phase as small δ' nearly spherical precipitates, T_1 (Al_2CuLi) and T_2 (Al_5CuLi) can precipitate in plate like morphology. The sizes and amounts of these phases are small and their characterization requires selected area diffraction pattern (SADP) and transmission electron microscopy (TEM) analyses. The localized precipitates in the metallographic analyses carried out are seen as

coarse Cu/Fe rich precipitates in a certain necklace type configuration in case of some Al-Li 2090 alloys. In addition, some of these precipitates could also be present in some case on secondary grain boundaries.

6. In Weldalite 049 type Al-Li-Cu-Mg-Ag alloys, other multiple phases such as T_1 and S' (Al_2CuMg) can coprecipitate with the δ' .
The additions of Ag and Mg are also considered to be giving another phase Λ. Additionally, T_2 and T_B ($Al_{7.5}Cu_4Li$) phases can precipitate. The several dislocation interactions with these multiple phases further affect the properties of these materials.

RECOMMENDATIONS FOR FURTHER WORK :

1. The SEM microprobe phase analyses should be carried out as far as possible to identify any phases without Li that possibly could be detected with these analyses .

2. The LOX impact compatibility would be related to the amount of Li and Cu and a critical ratio in these commercial alloys. These variants in chemistry should be analyzed to identify and understand these effects.

3. The LOX impact compatibility and the sensitivity at grain boundaries needs to be analyzed in more detail and in sufficient detail. For this DIC differential interference contrast microscopy can be further utilized.

4. The grain boundary effects and any sensitivity in these Al-Li alloys has been searched by some authors for effects of Na, K, and P. Ca and B could also be affecting the sensitivity behavior. This needs to be analyzed for any effects on LOX compatibility .

5. The effects and analyses of the several microconstituents in these commercial Al-Li alloys deserve further detailed study with microanalytical phase studies using TEM as necessary , and possibly with differential scanning calorimetry DSC techniques.

6. These above studies should be used to coorelate and completely understand the LOX impact compatibility of these newer and significant low density, high specific strength Al-Li alloys.

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