NASA Contractor Report 187631

Development and Characterization of Powder Metallurgy (PM) 2XXX Series Al Alloy Products and Metal Matrix Composite (MMC) 2XXX Al/SiC Materials for High Temperature Aircraft Structural Applications

D.J. Chellman, T.B. Gurganus, and J.A. Walker

Lockheed Aeronautical Systems Company
Research, Technology, and Engineering Division

Contract NAS1-16048
February 1992

National Aeronautics and
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FOREWORD

The following report documents the results of a series of material studies performed by the Lockheed Aeronautical Systems Company over the time period from 1980 to 1991. The technical objective of these evaluations was to develop and characterize advanced aluminum alloy materials with temperature capabilities extending to 350°F. This report is divided into two sections. The Executive Summary gives an overview of the first five alloy development efforts under this contract. Prior work conducted during the first five modifications of the alloy development program are listed in the references section. Section 3 of the report documents recent developments based on the addition of high Zr levels to an optimum Al-Cu-Mg alloy composition by powder metallurgy processing.

Both unreinforced, and SiC or B_4C ceramic reinforced alloys were explored to achieve specific target goals for high temperature aluminum alloy applications. The research study was conducted under the NASA-LaRC Contract No. NAS1-16048. D.M. Royster and W.D. Brewer were the NASA Program Managers on the recent development efforts.

The authors are grateful to H.C. Slaughter and M.B. Gibb of Lockheed for their conscientious contributions to the technical performance of this material characterization program. Acknowledgements are also given to the technical support personnel at the Alcoa Technical Center and Advanced Composite Materials Corporation (ACMC).

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SYMBOLS, ABBREVIATIONS, ACRONYMS

Symbol	Definition	Customary Engineering Units
AA	artificially aged	-
APD	average particle diameter	μ
B_4C_p	boron carbide particulate	-
CWQ	cold water quench	-
CY	calendar year	-
E_c	modulus of elasticity in compression	Msi
E, E_t	modulus of elasticity in tension	Msi
e	tensile ductility	pct.
ϵ	engineering strain	in./in.
ϵ_f	total engineering strain to failure ($\epsilon_e + \epsilon_p$)	in./in.
ϵ	effective extrusion strain	non-dim
$\dot{\epsilon}$	time-average strain rate	in./in.-sec
G.P. (B) Zones	pre-precipitation clusters of Cu atoms on Al cube plane	-
Hi-Cu	high copper	-
Hi-Mn	high manganese	-
Hi-Zr	high zirconium	-
HM	high elastic modulus	-
HR	hot rolled	-
hr	hour	-
HS	high strength	-
IM	ingot metallurgy	-
Δ K	stress intensity range	ksi-in.$^{1/2}$

SYMBOLS, ABBREVIATIONS, ACRONYMS

Symbol	Definition	Customary Engineering Units
K_{app}	apparent plane stress fracture toughness	ksi-in.$^{1/2}$
K_C	critical stress intensity factor	ksi-in.$^{1/2}$
K_{ICH}	Charpy fracture toughness	ksi-in.$^{1/2}$
K_{SC}	stress concentration factor	-
L	longitudinal grain direction	-
MMC	metal matrix composite	-
NA	naturallly aged	-
NTS	notched tensile strength	ksi
NTS/YS	notched tensile strength to yield strength ratio	non-dim
PA	artificially aged to peak strength condition	-
PM	powder metallurgy	-
ρ	density	lb/in^3
R	minimum to maximum fatigue stress factor	-
R_B	Rockwell B scale hardness	-
σ	engineering stress	-
s,sec	seconds	-
S	Al_2CuMg intermetallic precipitate equilibrium phase	-
S'	Al/Cu/Mg transition phase	-
SEM	scanning electron microscopy	-
SHT,ST	solution heat treatment	-
SiC_W	silicon carbide whisker	-

SYMBOLS, ABBREVIATIONS, ACRONYMS

Symbols	Definition	Customary Engineering Units
SiC_p	silicon carbide particulate	-
θ	Al_2Cu intermetallic precipitate	-
θ'	Al/Cu transition phase	-
θ''	ordered 2nd step G.P. zone formation (G.P. II)	-
T	transverse grain direction	-
TEM	transmission electron microscopy	-
TMT	thermomechanical treatment	-
w/o,wt.pct.	weight percent	-
YS	yield strength (0.2% offset)	ksi
UPE	unit propagation energy	in.-lb/in
WR	warm rolled	-

1.0 EXECUTIVE SUMMARY (MAY 1980 - SEPTEMBER 1985)

1.1 Introduction

The overall objective of the supersonic cruise vehicle (SCV) technology assessment studies is to identify the important research and development necessary to support decisions of national interest related to plans for future United States commercial air transportation. The paramount issue of the decision process is whether an ecologically suitable SCV can be developed with acceptable risk that will provide safe and profitable operation.

Pivotal concerns regarding any future SCV are noise, performance, cost, and development risk. Prior NASA contracts have focussed on many of these crucial issues. This report documents the development of higher temperature aluminum alloys which can offer better performance at lower cost than other materials.

Aluminum alloys are of interest for a SCV because of their relatively low cost and ease of fabrication. The availability of a work force familiar with aluminum, and the proper shop equipment for fabrication and assembly, also make aluminum an attractive structural material.

Supersonic cruise vehicles (SCV) speeds at Mach 2.0-2.3 will not generate temperatures in excess of aluminum alloy capabilities. The present conventional aluminum alloys are not structurally competitive with titanium for elevated temperature applications above 250°F. However, the advent of aluminum rapid solidification (RS), powder metallurgy (PM), advanced alloy developments, and improvements in mill processing show exceptional promise for producing affordable elevated temperature aluminum mill products for 250°-350°F applications.

Lockheed has established a working relationship with ALCOA and INCO to synthesize these advanced alloys and evaluate their performance. A family of alloys is being studied with the individual members being tailored to different design requirements. The specific alloy types are high strength, damage tolerant, high modulus, and low density.

1.2 Background

Precipitation hardening aluminum alloys have been widely used in the aerospace industry because of their relatively low raw material and fabrication costs, and the ability to develop satisfactory specific strengths for sub-sonic applications. For sustained use in the Mach 2.0 to 2.4 supersonic range, however, conventional aluminum alloys have presented several serious drawbacks. First, conventional aluminum alloys are not as efficient as titanium for many structural applications. Second, development of a high strength aluminum alloy having good thermal stability at the elevated temperatures created above Mach 2.2 speeds have been lacking. As a result, airframe designers have been forced to either accept the penalties associated with these materials or to look for alternate materials for supersonic transport structures.

Studies conducted by the aircraft industry under funding by NASA have indicated that the airframe of a supersonic transport aircraft operating above Mach 2.2 would contain approximately 70 percent titanium alloys.(1) This is due to the good stability of titanium in the temperature range of 300^{o} to 500^{o}F where a Mach 2.2 transport would operate. Below Mach 2.2, supersonic transport structures are exposed to more moderate temperatures in the range of 225^{o} to 275^{o}F. At these temperatures, aluminum alloys can be considered for airframe structure. For example, a significant amount of 2618 aluminum is incorporated in the supersonic Concorde, which cruises at a speed of Mach 2.02. However, the strength-to-density ratio of 2618 aluminum is not competitive with titanium alloys.

Potentials for increasing the temperature of aluminum materials are appearing from recent research in powder metallurgy, advanced alloy synthesis, and improved mill processing. Advancements in aluminum technology, particularly in rapid solidification and powder metallurgy, offer new approaches for development of improved alloys with high strength, high toughness, improved corrosion resistance and fatigue life, and greater heat resistance than conventional alloys.

1.3 Approach

The overall goal of these structural materials studies is to identify and conduct the development efforts necessary to support decisions related to plans for future United States high speed aircraft systems. A major portion of the technology studies focussed on the development and evaluation of advanced aluminum (Al) alloy materials. Since late 1970, the Lockheed Aeronautical Systems Co. (formerly known as the Lockheed-California Co.) has been developing of a family of improved Al alloys in conjunction with several Al producers. The research efforts have been directed toward the identification, fabrication, and characterization of a family of rapid solidification (RS), powder metallurgy (PM) Al alloys tailored to satisfy four specific design properties. The four specific design properties include high strength, damage tolerance and fatigue resistance, high modulus, and low density(2). Target material properties are shown in Table 1 for the four applications.

Note that the high stiffness and low density goals are the same, except for specific stiffness requirements, and will probably be met by the development of a single aluminum-lithium alloy. ALCOA is addressing both the high strength and damage tolerant alloys, and INCO is developing the high strength and the high modulus, low density alloys. The alloy development tasks for the sub-contractors are discussed below.

Requirements	Units	High Strength Corrosion Resistance		Damage Tolerance	High Stiffness	Low Density	High Strength High Modulus
		A	B				
Strength	Ftu - ksi	84	75	68	62	62	85
	Fcy - ksi	82	73	62	55	55	78
Fatigue*	Fmax - ksi	23	21	30	19	19	23
	Δ K - ksi- in1/2	6.2	5.6	7.2	5.6	5.6	6.2
Fracture	Kapp - ksi in1/2	60	60	81	60	60	60
Toughness	KIC ksi in.1/2	26	26	30	26	26	26
Density	lb/cu. in.	0.101	0.094			0.09	0.101
Elastic Modulus	Msi	10.5	12.4	10.7	11.8	11.8	15.6
Corrosion Resistance							
Stress Corrosion - ksi		25	25	25	25	25	25
Exfoliation Corrosion		>EA	>EA	>EA	>EA	>EA	>EA

NOTES:

*Fmax at 1E5 Cycles, Kt=3, R=0.1

Δ K for R=0.1. DA/DN 1E-6 in./in., 95 pct. Relative Humidity

Elevated temperature properties

Stability - room temperature properties unaffected

Greater than 80% of RT properties in the range of 250°-350° F

5% elongation set as target goal

Greater than 18 ksi creep strength for 0.1 percent creep strain in aircraft life.

Table 1. Target Goals for Individual Design Criteria.

A family of advanced aluminum alloys is being developed under sub-contract to Lockheed by the Aluminum Company of America (ALCOA) and the International Nickel Company (INCO). The research goals of these sub-contractors are to develop a family of alloys that have specific properties comparable to titanium alloys. The ALCOA program is exploiting the advancements in aluminum technology, particularly rapid solidification (RS), powder metallurgy (PM), for development of improved corrosion resistance and fatigue life, and greater heat resistance than conventional ingot metallurgy (IM) aluminum alloys. The ALCOA effort is focussing on the high strength alloy and the damage tolerant alloy development. The INCO program is initially directed toward mechanical alloying and to establish the potential roles of several alloying elements in materials intended for elevated temperature service. INCO is addressing the high strength, corrosion resistant alloy and the high modulus, low density alloy development goals.

2.0 SUMMARY OF RESULTS AND PROGRESS

2.1 First Iteration Development Studies

Preliminary results from ALCOA development efforts on a damage tolerant alloy system indicate that the primary toughness goals have been exceeded with K_{IC}/K_Q values up to 54 ksi-in.$^{1/2}$ and notch-yield ratio values in excess of 1.5. However, the tensile properties were slightly below the 68 ksi ultimate and 62 ksi yield goals. It is very probable that some toughness can be traded for strength, if necessary. Fatigue improvements from 8 to 33 pct. were obtained. Strength retention at elevated temperatures is adequate with 80 pct. of room temperature properties maintained at 250^{o}F. Transverse properties are excellent for both ductility and toughness.(3)

INCO work on the high strength, corrosion resistant alloys is showing promising results. The current alloy compositions do not meet the 84 ksi goal, but the experimental data provides a basis for estimating the alloy content required to reach that goal. Toughness was adequate with notch-yield ratios approaching 1.27.

A significant increase in toughness is realized through increased extrusion temperatures with only small reductions in strength. These results indicate that an alloy meeting the high strength goals may be possible by increasing the alloy content. Strength retention at elevated temperatures was encouraging with promising alloys attaining greater than 80 pct. of room temperature properties at 250°F.(3)

Prior research conducted by INCO on mechanically alloyed (MA) aluminum had shown that many of the alloying effects seen in conventional alloys are altered in oxide dispersion strengthened, mechanically alloyed materials. For this reason it was desirable to re-evaluate basic alloying effects prior to the development of new alloys. For example, early efforts to impose mechanical alloying on alloys of conventional heat-treatable compositions yielded excessively hard materials which did not respond to heat treatment in the usual way. In view of this behavior, and because only cursory evaluations of mechanically alloyed materials have been carried out at elevated temperature, the main thrust of this work was to establish the potential roles of several alloying elements in materials intended for elevated temperature service. The approach was to determine useful combinations of strengthening through oxide dispersion and other mechanisms, i.e., dispersions of metallic constituents and solid solution strengthening.

The alloying elements used for studying the present mechanical alloying work include: Fe, Fe + Mn, Fe + Co, Li, and Si. Li is well known for its beneficial effects on elastic modulus and density of aluminum alloys, however, its influence in mechanically alloyed materials at elevated temperatures have not been evaluated. Prior work at INCO on materials with Fe + Mn and Fe + Co additions showed improved strength at elevated temperatures. Si in aluminum alloys is generally minimized because, when present as large particles precipitated from the melt, it causes brittleness. However, in mechanically alloyed materials where the particle size of Si could be made small, it is postulated that brittleness may not be encountered.

Thus, the very high melting point of Si and its low solubility in aluminum could confer stability through the fine dispersion of Si particles produced by mechanical alloying and provide strength at elevated temperatures.

ALCOA is directly addressing two (2) of the four (4) sets of property goals that were established. In terms of the current effort, it was believed that the high modulus goal and low density goal would be adequately explored by other government programs, and therefore, a "wait and watch" attitude was adopted. The high strength goal was treated to some extent in the Air Force Materials Laboratory elevated temperature aluminum alloy development program initiated in early 1981. However, this work was primarily directed toward service applications at much higher temperatures (minimum of 450^{o}F) and shorter service life. Therefore, additional work was programmed for development of high strength aluminum alloys to be used at more moderate temperatures for extended periods of time. The two (2) materials that were considered to be the most likely candidates for this application were Al-Cu-Mn and Al-Cu-Mg-(Mn) powder metallurgy (PM) alloys.

The PM Al-Cu-Mn alloy, containing roughly equivalent amounts of Cu and Mn, was identified in internal ALCOA programs as an excellent candidate for moderate elevated temperature applications where high strength is required. This represents primarily a dispersion hardening alloy concept, however, at high Cu/Mn ratios, precipitation hardening could be a factor. Little is known about most of the secondary mechanical properties of this system, so initial efforts will be exploratory to build a data base on the properties of PM Al-Cu-Mn alloys with widely varying fabricating procedures and compositions.

The PM Al-Cu-Mg-(Mn) alloys are candidates for filling the damage tolerant goal. Al-Cu-Mg-(Mn) alloy products fabricated using ingot metallurgy (IM) techniques have long been used in naturally aged tempers for room temperature, damage tolerant applications. However, artificially aged tempers are required for elevated temperature service and when aged to this condition, toughness and fatigue properties are poor.

It is believed that an improvement in this situation can be obtained through the use of the PM process. Properly applied, this process has been demonstrated to improve both toughness and notched fatigue life for 7XXX aluminum alloys. Because a combination of 2XXX alloying and PM processing has not been tested to any large extent, this effort was also exploratory in examining PM versions of a high Cu content 2618 and alloy compositions similar to 2124.

Conclusions - First Iteration Development Studies (3)

- o A decided improvement in damage tolerant characteristics can be readily attained with PM aluminum alloy technology. Continued development is still required to optimize the PM alloy composition and processing to achieve the combination of properties required for damage tolerant supersonic design.

- o The high strength alloy development endeavor has not yet produced an alloy which possesses the overall properties necessary for supersonic performance. Alloys which met the high strength targets failed in ductility. Problem areas have been identified and resolution efforts are proceeding.

Damage Tolerant Alloy Development

- o PM processing of 2XXX alloys significantly improved fracture toughness (Figure 1) and fatigue crack initiation resistance.

- o Results indicate damage tolerant goals including strength, toughness, stability, and corrosion resistance can be met using PM technology (Figure 2).

- o PM processing of 2124 naturally aged extrusions developed significant strength improvements over comparable IM products.

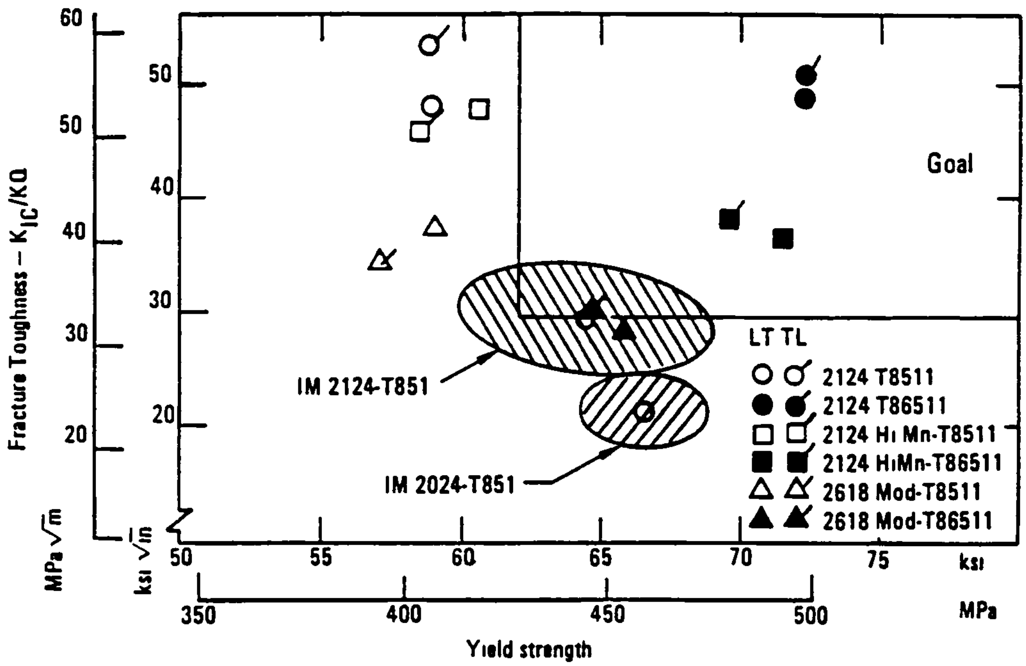


Figure 1. Fracture Toughness Versus Yield Strength of Damage Tolerant PM 2XXX Alloys.

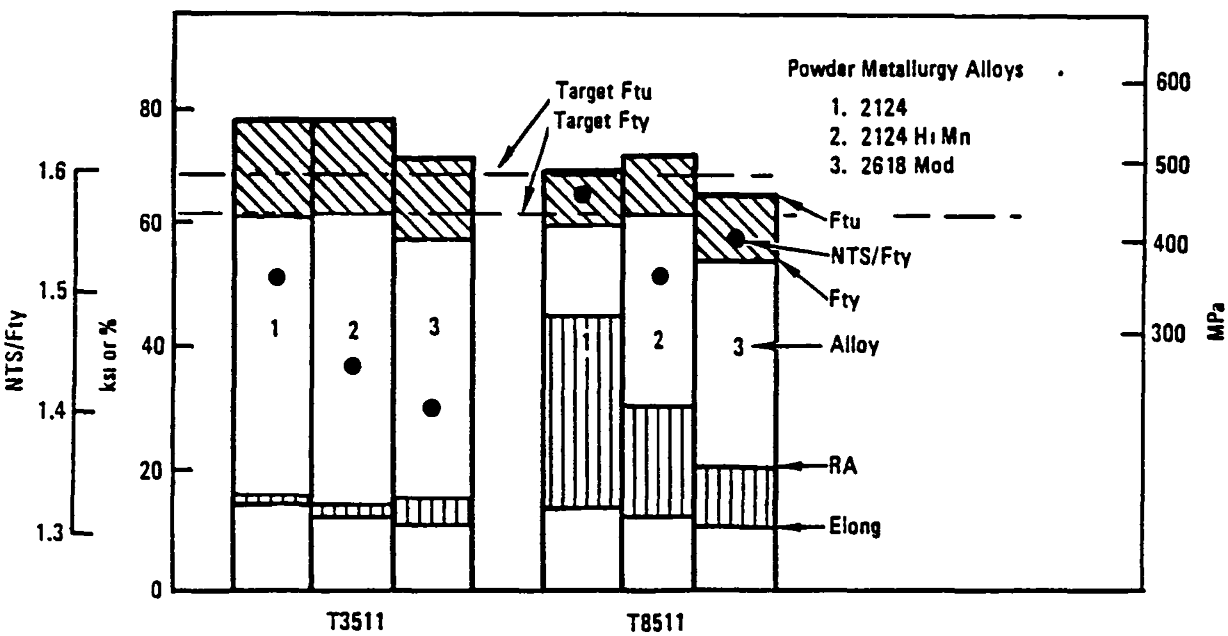


Figure 2. Comparison of Properties of Damage Tolerant Aluminum Alloy Extrusions, Longitudinal Orientation.

In contrast, the strength of artificially aged tempers of PM products was equivalent to that of IM (Figure 3).

- Fatigue goals were met in the -T3X tempers, however, artificial aging, required for elevated temperature applications, resulted in lower fatigue properties (Figure 4). Although part of the property reduction may be explained by associated tensile strength reduction, further work is required to understand the mechanisms involved and to determine possible approaches to obtain the required improvements in artificially aged tempers.

- Elevated temperature aging had little effect on K_Q behavior of 0.75 in. thick compact tension specimens. Crack growth resistant (K_R) behavior was reduced by artificial aging, nevertheless, the crack growth resistance of the artificially aged PM products still exceeded that of IM products by significant margins.

- PM processing of 2124 and 2124 - High Mn altered the reaction kinetics resulting in shorter aging times for precipitation hardening and increased reduction in strength on long time exposure to temperatures over 250°F.

- Further work is required to determine the effect of PM processing on properties of 2618 modified extrusions. Excessive Cu content of the first iteration 2618 modified alloy resulted in extensive precipitation of the Al_7Cu_2Fe phase, which by reducing available Cu contents and increasing dispersoid levels, probably contributed to reductions in strength, toughness, and fatigue.

- Current knowledge concerning phase relationships, metastability of alloy microstructures, and microstructure-property relationships in PM alloys is inadequate for expeditious alloy/process optimization.

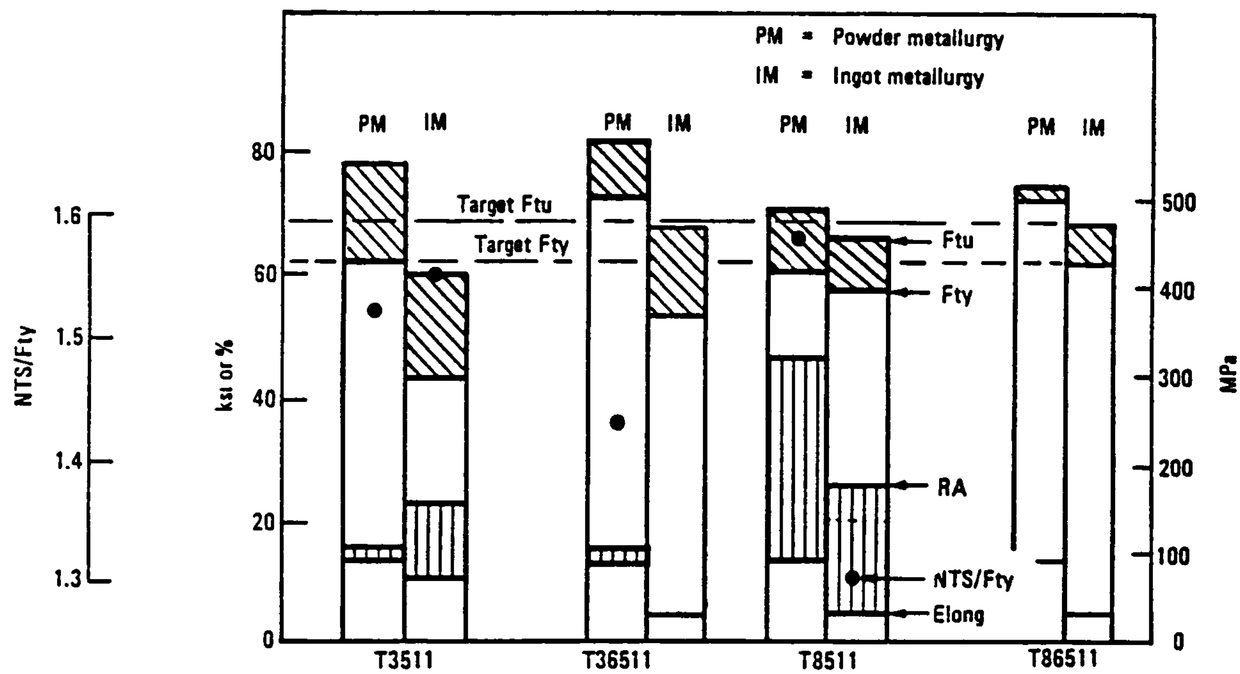


Figure 3. Effect of Heat Treatment on Properties of Damage Tolerant Aluminum Alloy 2124 Extrusions, Longitudinal Orientation.

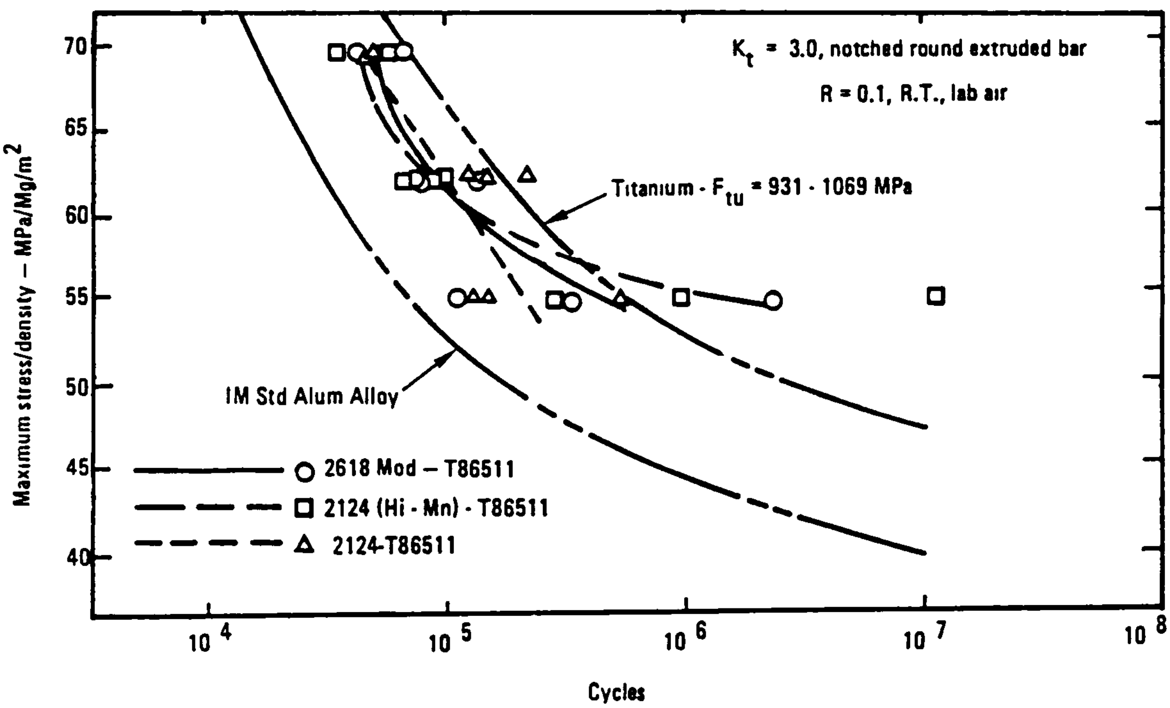


Figure 4. Constant Amplitude Axial Notched Fatigue of PM 2XXX- T86 Extrusions.

- The fatigue crack growth resistance of PM 2XXX-T86511 under constant amplitude loading in humid air was equivalent to IM 2024-T851 plate at high stress intensities and lower than that of IM 2024-T851 plate at lower stress intensities (Figure 5). Further data is required on R ratio, frequency, environment, and spectrum (overload) effects in order to assess the impact of the fatigue crack growth behavior of PM alloys on airframe design.

- Although properties of PM alloys were only slightly reduced by 1000 hr. exposure at 250°F, further work is required to ensure suitability of the alloy systems for 50,000 hr. exposure under stress and unstressed conditions (Figure 6).

High Strength Alloy Development

- Achievement of strength goals through mechanical alloying with transition elements will require a substantial increase in solute level, i.e., 5 to 6 atomic percent (Figures 7 and 8).

- Mechanical alloyed Al-Fe-X systems of low solute level (1.5-2.0 atomic percent) are more stable than equivalent high solute level PM systems. This difference can be attributed to the greater stability of the Al_2O_3 and Al_4C_3 dispersoids and the higher hot compaction temperature (950°F) used in processing of the mechanically alloyed systems.

- Tensile ductility of mechanically alloyed Al-Fe-X systems decreased with increasing test temperature.

- Further work is required to optimize mechanical attritor processing of mechanical alloys to improve homogeneity.

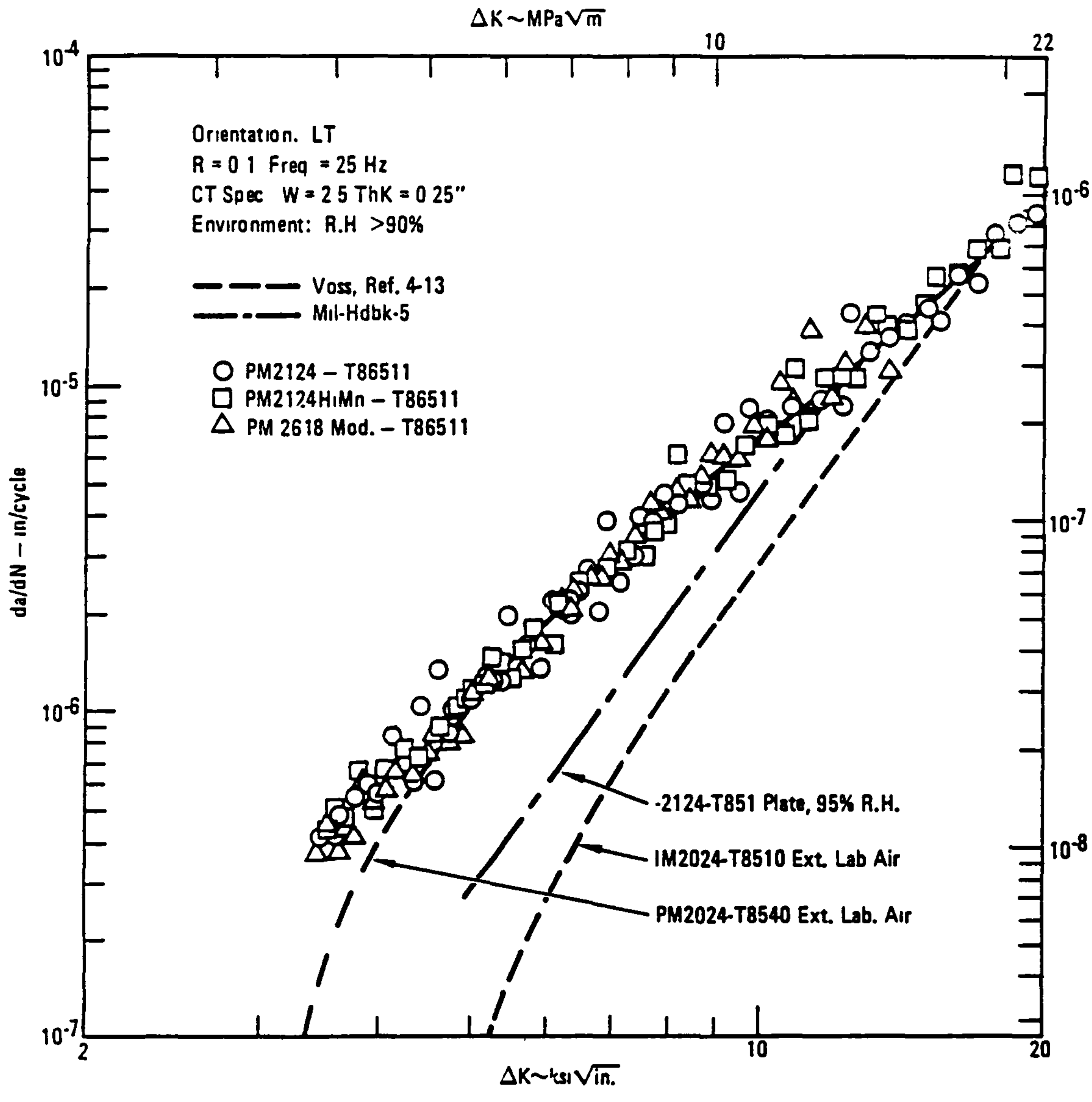


Figure 5. Comparison of Fatigue Crack Growth Behavior of PM 2XXX-T86 Damage Tolerant Aluminum Alloy Extrusions.

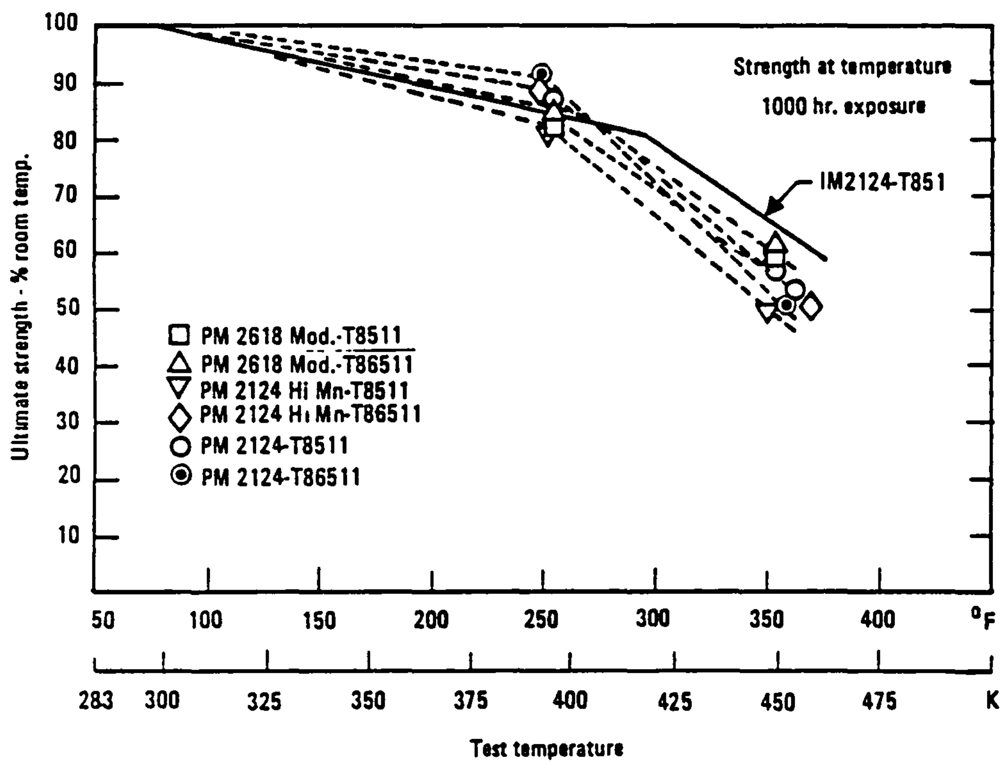


Figure 6. Effect of Temperature on Strength of 2XXX Damage Tolerant Aluminum Alloy Extrusions.

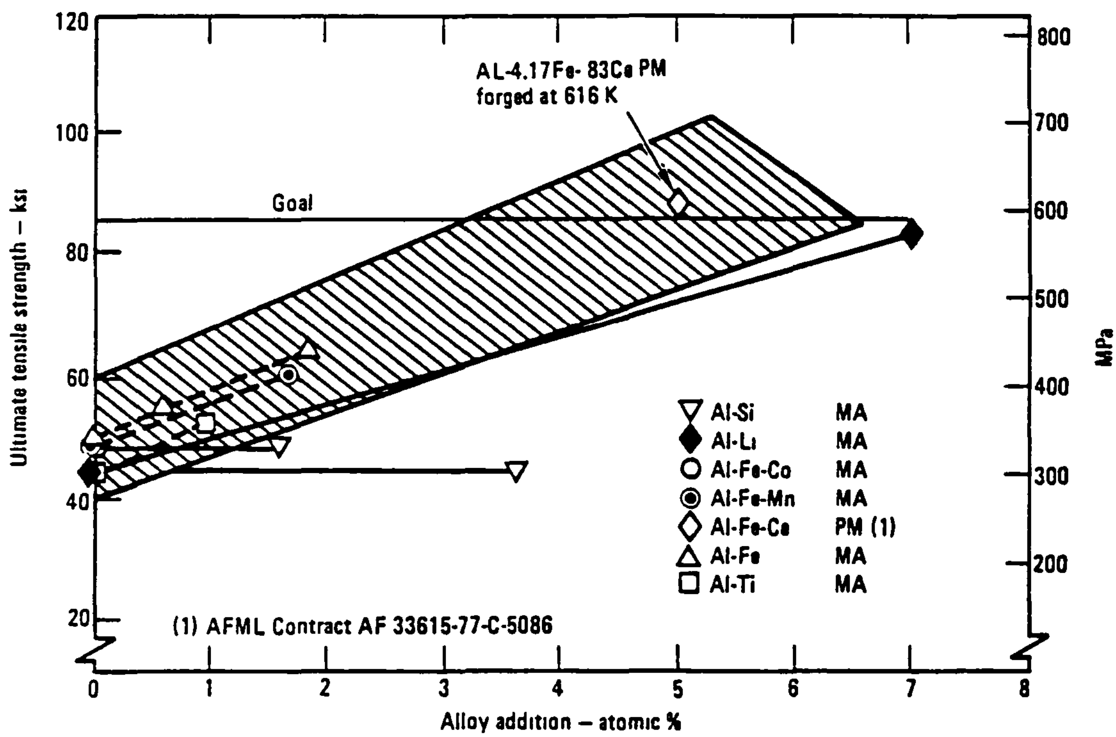


Figure 7. Effect of Alloy Content on Strength of High Strength Aluminum Alloys.

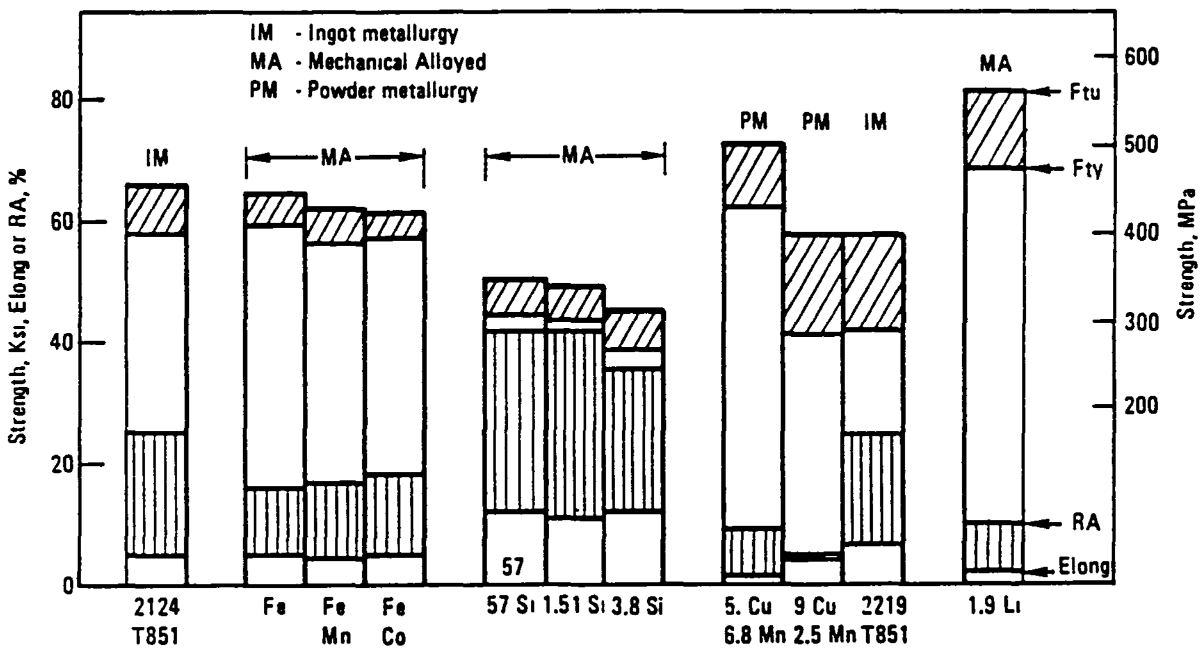


Figure 8. Comparison of Tensile Properties of High Strength Aluminum Alloys.

- o Mechanically alloyed Al-Li alloy systems met specific strength goals, but further work is required to improve ductility and stability (Figure 8).

- o Dispersion strengthened/precipitation hardened PM Al-Cu-Mn systems required extremely low temperature processing to meet strength goals. Further work is required to resolve the resulting problem of brittle behavior.

2.2 Second Iteration Development Studies

This series of development work describes the analytical and test work completed by Lockheed on the second iteration of high temperature aluminum alloy materials. The current development efforts include continuing studies and cover three (3) types of metallurgical systems. The reinforcement of 2XXX series Al alloys with SiC was added to the development efforts during the recent reporting period.(4) A summary of the research work for two (2) unreinforced Al alloy systems involves mechanical alloying and powder atomization.

Mechanically Alloyed Powder Metallurgy

In this continuing study, the development of mechanically alloyed heat resistant Al alloys for aircraft was directed toward higher strength targets and higher service temperatures. The use of higher alloy additions to MA Al-Fe-Co alloys, employment of pre-alloyed starting materials, and higher extrusion temperatures were investigated. While the MA Al-Fe-Co alloys exhibited good retention of strength and ductility properties at elevated temperatures and excellent stability of properties after 1000 hr. exposure at elevated temperatures, a sensitivity of this system to low extrusion strain rates adversely affected the level of strength achieved. MA alloys in the Al-Li family showed excellent notched toughness and property stability after long time exposures at elevated temperatures.

A loss of Li during processing and the higher extrusion temperature of 900°F resulted in low mechanical strengths. Subsequent hot and cold working of the MA Al-Li had only a mild influence on properties.

The advantage of using pre-alloyed powders as a starting material, while producing cleaner structure, could not be clearly established because of the attritor processing anomalies encountered and because of the changes in thermomechanical processing conditions.(4)

Attempts to mechanically alloy the Al-Fe-Ce alloy were unsuccessful. A greater in-depth study of processing parameters will be required to establish appropriate attritor conditions.

MA Goal Realization

- The MA Al-Fe-X alloy systems explored so far have not attained the room temperature strength improvements required to effect an aluminum design competitive with titanium alloys. Present work showed no improvement over earlier efforts relative to attaining ultimate strength. The alloy system has displayed a thermally stable matrix (after 1000 hr. exposure) and less than a 25 pct. drop in strength after 350°F, the upper temperature limit of this program.

- The MA Al-Li system displayed a similar behavior to the Al-Fe-X system in that room temperature strength was below target goals. Thermal exposure up to 1000 hr. had negligible effects on strength stability, however, this alloy system had a loss in strength at temperature of approximately 50 pct. at 350°F.

Powder Metallurgy

Six (6) powder metallurgy extruded materials were studied in the recent development iteration. PM 2618 modified alloys originally tested and reported in previous efforts, received follow-on optical, scanning electron microscopy, and pinhole X-ray diffraction evaluations. The ALCOA atomization, compaction, consolidation, and extrusion sequence was used to produce a new set of test materials, involving PM Hinduminium, PM 2618, and PM 2618 modified compositions. The promise of elevated temperature property improvement based on published data was the basis for selection of these three (3) new alloys. Composition, X-ray crystallographic, optical metallographic, and precipitation hardening studies were conducted for the new materials. Ambient property comparisons were made for the six (6) materials of this project and they were further compared with other ingot and powder metallurgy members of the 2XXX Al alloy family.(4)

PM Goal Realization

- At ambient temperature, the peak-aged ultimate strength of the 6.0 pct. stretched PM 2618 modified alloy meets the design minimum target value for damage tolerant application, while the other PM Hinduminium and PM 2618 materials approach but do not meet the target value. However, none of these three (3) materials provided ambient strength improvements over conventional ingot metallurgy 2XXX materials to the extent provided by the PM 2124 modified alloys introduced earlier in this project. Temperature stability has not yet been tested for the new materials although the body of aging study data suggests that the PM 2618 alloy derivative may have slightly greater stability than the PM 2124 compositions.

- The PM HID 543 modified alloy material showed a marked decline in maximum obtainable strength with increasing aging temperature. PM 2618 type alloys were more stable and were therefore selected for on-going studies. Two step aging did not show a strength gain over single step aging for the PM 2618 alloy candidates. The PM 2618 candidates joined the PM 2124 alloys tested earlier in showing fracture toughness improvements over IM 2124.

- Toughness of the PM 2124 type materials tested earlier exhibited decreases with increased dispersoid and constituent content, with fractography showing a corresponding finer and closer packed dimple distribution on the fracture surfaces.

- Thermal stability, fracture toughness, corrosion resistance, and fatigue resistance are to be concluded for the PM 2618 materials in the follow-on activity.

- An increase in dispersoid content resulted in a modest 15 pct. increase in strength, but with a slight decrease in ductility.

- Excellent notched toughness and ductility properties were obtained in the MA Al-Li alloys. The notched toughness was not affected by subsequent hot or cold working procedures.

- Hot working up to 25 pct. reduction after extrusion has no significant effect on properties, yielding a mild increase in ductility combined with a slightly strength reduction.

- An intermediate cold work (up to 25 pct.) improved strength levels and slightly reduced tensile ductility.

- The MA Al-Li alloys retained approximately 75 pct. of their strength after testing at 250°F, but only 50 pct. at 350°F. Ductility improved as test temperatures were increased.

- Long time exposure (1000 hr.) at elevated temperatures had no significant influence on the strength and ductility properties of the MA Al-Li alloys.

PM 2XXX Al Alloys

- The strength of the PM Al alloys is dependent on the solute content and amount of cold work applied prior to aging. The addition of Fe and Ni to the 2618 base composition is shown to reduce the yield strength is attributed to the formation of the fine, uniformly distributed Al_7Cu_2Fe constituent, instead of strictly Al_9FeNi. The Mg modified PM 2219 alloy displayed the lowest strength of the alloys investigated, perhaps due to the low solution heat temperature.

- An increase in the amount of cold work by stretching improves the naturally aged yield strength of the Fe and Ni free, high Cu 2618 alloy. In the artificially aged temper, the strength advantage is lost because of the nominally lower solute content.

Conclusions - Second Iteration Development Studies (4)

MA Aluminum Alloys

Al-Fe-Co Alloys

- Strength and notched sensitivity at ambient temperature increase with a decrease in extrusion temperatures.

- MA Al-Fe-Co alloys exhibit good retention of strength and ductility properties after long time exposure (1000 hr.) at both 250° and 350°F.

- At 250°F, MA Al-Fe-Co alloys exhibit strength losses of less than 20 pct. even after 1000 hr. exposure. At 350°F, strength losses of less than 25 pct. were obtained, even after 1000 hr. exposure.

- The generally lower strength levels observed is believed to be caused by the lower extrusion strain rates. This lower strain rate is due to the combined effects of changes in billet size and extrusion bar geometry, coupled with a lower extrusion ratio and reduced extrusion speed.

- Pre-alloyed starting materials resulted in cleaner extruded bar structures. However, the use of pre-alloyed powders may affect the type of dispersoid formed, which in turn, may have an adverse influence on strength.

Al-Li Alloys

- A significant loss in Li content, from 1.7 to approximately 1.0 wt. pct., was observed. This behavior, coupled with the higher extrusion temperature, is believed to contribute significantly to the low strength levels. An increase in dispersoid content resulted in a modest 15 pct. increase in strength, with a slight decrease in ductility.

- Excellent notched toughness and ductility properties were obtained in the MA Al-Li alloys. The notched toughness was not affected by subsequent hot or cold working procedures.

- Hot working up to 25 pct. reduction after extrusion had no significant effect on properties, yielding a mild increase in ductility combined with a slight strength reduction.

- An intermediate cold work (up to 25 pct.) improved strength levels and slightly reduced tensile ductility.

- The MA Al-Li alloys retained approximately 75 pct. of their strength after testing at 250^{o}F, but only 50 pct. at 350^{o}F. Ductility improved as test temperatures were increased.

- Long time exposure (1000 hr.) at elevated temperatures had no significant influence on the strength and ductility properties of the MA Al-Li alloys.

PM 2XXX Al Alloys

- The strength of the PM Al alloys is dependent on the solute content and amount of cold work applied prior to aging. The addition of Fe and Ni to the 2618 base composition is shown to reduce the yield strength in natural and artificial aged tempers. The loss in strength is attributed to the formation of the fine, uniformly distributed Al_7Cu_2Fe constituent, instead of strictly Al_9FeNi. The Mg modified PM 2219 alloy displayed the lowest strength of the alloys investigated, perhaps due to the low solution heat temperature.

- An increase in the amount of cold work by stretching improves the naturally aged yield strength of the Fe and Ni free, high Cu 2618 alloy. In the artificially aged temper, the strength advantage is lost because of the nominally lower solute content. An attempt to improve the strength by a two step aging treatment was unsuccessful.

- The notched tensile ratio versus yield correlation of the PM 2618 modified alloys is similar to the low Mn PM 2124 alloy, which exhibits a 10-15 pct. improvement in toughness over IM 2124 at similar strengths (Figure 9). The lower notched strength of the Mg modified 2219 alloy is probably due to the coarse Al_2Cu particles which remain after solution heat treatment. Fractography of the PM 2124 pre-cursors reveals that the decrease in toughness which results from increasing the dispersoid or constituent volume fraction by artificial aging is associated with a finer dimple size and spacing.

- The improvement in fatigue resistance of IM 2124 obtained by PM processing is shown by SEM fractography, although microstructural constituents responsible for crack initiation were not detected. Optical metallography suggests that the large variation in the fatigue life in the naturally aged tempers is due to different specimen locations in the extrusion. The shortest fatigue life was associated with a finer grain structure and large amounts of inclusions observed at the rear of the extrusion as opposed to the front.

- Contingent on results of elevated temperature testing and fracture toughness, the higher strengths of the initial PM 2124 modified alloys appear more promising than the most recently tested PM 2219 and 2618 alloys.

2.3 Third Iteration Development Studies

The objective of the present investigation involves an improvement in the strength and fracture toughness combination of PM 2124 Al alloys in accordance with NASA program goals for damage tolerance and fatigue resistance.(5) Two (2) PM compositions based on Al-Cu-Mg-(Mn) with 0.12 and 0.60 wt. pct. Zr were selected for examination.

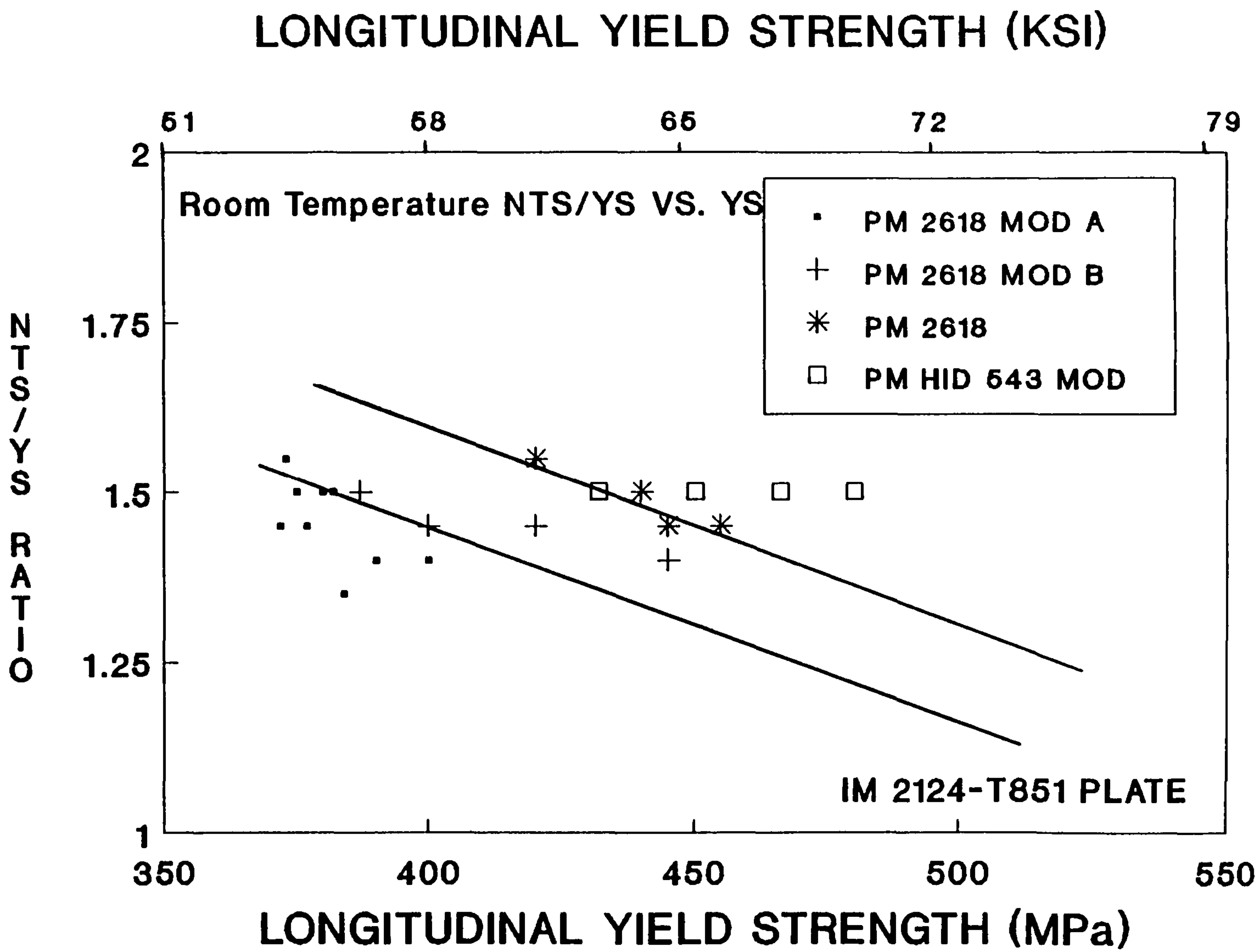


Figure 9. Notched Tensile Strength/Yield Strength Ratio Correlation of PM 2XXX Alloys Compared to IM and Previous PM 2124 Aluminum Alloys.

The rapid solidification rates produced by atomization were observed to prohibit the precipitation of coarse, primary Al_3Zr in both alloys. A major portion of the Zr precipitated as finely distributed, coherent Al_3Zr phases during vacuum pre-heating and solution heat treatment. The proper balance between Cu and Mg contents eliminated undissolved, soluble constituents such as Al_2CuMg and Al_2Cu during atomization. The resultant extruded microstructures produced a unique combination of strength and fracture toughness. An increase in the volume fraction of coherent Al_3Zr, unlike incoherent $Al_{20}Cu_2Mn_3$ dispersoids, strengthened the PM Al base alloy either directly by dislocation-precipitate interactions, indirectly by a retardation of recrystallization, or a combination of both mechanisms. Furthermore, coherent Al_3Zr does not appear to degrade toughness to the extent that incoherent $Al_{20}Cu_2Mn_3$ does. Consequently, the addition of 0.60 wt. pct. Zr to the base alloy, incorporated with a 935^{o}F solution heat treatment temperature, produces an alloy which exceeds all tensile property and fracture toughness goals for damage tolerant and fatigue resistant applications in the naturally aged condition. These PM 2124-Zr modified alloys display superior mechanical properties when compared to both other PM 2124 Al alloys, and an experimental IM 2124 composition with 0.12 wt. pct. Zr.

The achievement of improved property combinations for Al alloys applicable to supersonic aircraft structures has been demonstrated on two (2) previous NASA-LaRC research programs by employing alloy modifications and PM processing.(3,4) For damage tolerant and fatigue resistant goals, an attractive combination of tensile strength, fracture toughness, and fatigue properties was displayed by PM composition variations based on 2124, 2618, and 2219 type Al alloys. In particular, research activities in cooperation with ALCOA have demonstrated the outstanding strength-toughness relationship available with extruded PM 2XXX series Al alloys. The following problem areas were identified in the previous studies with respect to attainment of the damage tolerant and fatigue resistant target objectives: (1) low strength levels for PM 2618 and 2219 Al alloys at room temperature,

(2) reduction of fracture toughness in PM 2618 and 2124-Mn modified alloys, (3) loss of notched fatigue strengths in artificially aged tempers, (4) degradation of elevated temperature and stability properties for PM 2XXX series Al alloys at 350°F. These property results suggest that a complex compositional relationship exists between precipitate and dispersoid strengthening, elevated temperature environments, and fracture toughness combinations.

The Al-Cu-Mg alloys based on the 2124 type Al alloy composition presently demonstrate the most promising combinations with respect to the damage tolerant and fatigue resistant goal. For this reason, the primary objective of the present study is to explore an improvement in strength and fracture toughness properties by employing alloy modifications to eliminate incoherent dispersoid and undissolved soluble constituent phases. Recent alloy development studies in the literature indicate that Zr additions are particularly effective in contributing to a fine grained and unrecrystallized microstructure in Al alloy extrusions. The effect of work content and heat treatment condition on property combinations is certain to be as important for the candidate PM 2124-Zr modified alloys as in previous Lockheed studies. A re-examination of the potential for PM 2219 or Al-Cu alloys to meet target goals was undertaken by using an optimum solution heat treatment schedule.

Conclusions - Third Iteration Development Studies (5)

- The rapid solidification rates produced by atomization prohibit the precipitation of coarse, primary Al_3Zr in PM 2124-Zr modified alloys that contain as much as 0.60 wt. pct. Zr. Most of the Zr forms as a finely distributed coherent Al_3Zr phase.

- An increase in the volume fraction of dispersoid produces only a subtle decrease in grain size and degree of recrystallization in extruded PM 2XXX Al alloys.

It is suggested that this behavior may be a result of an extremely effective distribution of oxide particles in all PM Al alloys. On an equal volume fraction basis, coherent Al_3Zr phases appear to be slightly more effective than incoherent $Al_{20}Cu_2Mn_3$ in retarding recrystallization.

- An increase in the volume fraction of Al_3Zr, unlike $Al_{20}Cu_2Mn_3$, strengthens the PM Al-3.70Cu-1.85Mg alloy without significantly reducing fracture toughness levels. An addition of 0.60 wt. pct. Zr to the base Al-Cu-Mg alloy, incorporated with a 935°F solution heat treatment temperature, produced an alloy that exceeds all tensile property and fracture toughness goals for damage tolerant and fatigue resistant applications in the natural aged condition (Tables 2 and 3). The behavior of the PM 2124-Zr modified alloys exceeded the properties of PM 2124 and an experimental IM 2124 alloy with 0.12 pct. Zr (Figure 10).

- The room and elevated temperature strengths after exposure to 250°F for 100, 1000, and 10,000 hr. are not sensitive to the volume fraction of incoherent dispersoids present in PM 2XXX Al alloys evaluated to date.

2.4 Fourth Iteration Development Studies

The objective of the present study is to fabricate and evaluate PM 2124 Al alloy plate and sheet materials in accordance with NASA program goals for damage tolerance and fatigue resistance.(6) Previous research has indicated the outstanding strength-toughness relationship available with PM 2124 Al-Zr modified alloy compositions in extruded product forms. The range of processing conditions was explored in the fabrication of plate and sheet gauge materials, as well as the resultant mechanical and metallurgical properties.

SAMPLE ID NUMBER	TEMPER	YIELD STRENGTH MPa	(KSI)	TENSILE STRENGTH MPa	(KSI)	El. %	R A. %
513707 (6)	NA	384	55.7	484	70.2	12.0	--
	PA (1)	407	59	455	66.0	10.0	--
513708 (6)	NA	420	60.9	520	75.4	10.0	--
	PA (2)	453	65.7	494	71.7	12.0	--
513709 (6)	NA	419	60.8	518	75.1	16.0	--
	PA (2)	451	65.4	497	72.0	12.0	--
513887 (8)	NA	383	55.4	498	72.3	14.5	14.5
	PA (3)	436	63.2	514	74.5	13.7	33.3
513888 (7)	NA	360	52.2	470	68.1	16.0	13.2
	PA (4)	364	52.8	420	60.9	13.0	41.5
513889 (7)	NA	388	56.2	506	73.3	16.0	15.2
	PA(5)	418	60.6	471	68.3	12.7	28.0
514041 (9)	NA	438	63.5	536	77.6	17.5	19.5
	PA(5)	493	71.4	532	77.2	14.0	34.0
514042 (9)	NA	463	67.2	571	82.8	15.0	19.0
	PA(5)	509	73.8	548	79.5	11.0	27.0
503315 (9)	NA	442	64.1	572	82.8	14.0	13.0
	PA (5)	529	76.8	575	83.4	11.0	28.0

NOTES:

(1) Aged 12 hours at 464 K (375 F)
(2) Aged 4 hours at 464 K (375 F)
(3) Aged 4 hours at 450 K (350 F)
(4) Aged 8 hours at 464 K (375 F)
(5) Aged 4 hours at 464 K (375 F)
(6) Solution heat treated at 766 K (920 F)
(7) Solution heat treated at 772 K (940 F)
(8) Solution heat treated at 802 K (985 F)
(9) Solution heat treated at 775 K (935 F)
(10) Stretched 1.5-2.0%

Table 2. Tensile Properties of PM 2XXX Al Alloy Extrusions.

SAMPLE ID NUMBER	TEMPER (7)	YIELD MPa	STRENGTH (KSI)	K(Q) MPa (m)1/2	K(Q) ksi (in)1/2	25 % SECANT VALUE MPa (m)1/2	ksi (in)1/2
513707	NA	384	55.7	42.2	38.4 (1,3)	71.3	64.9
	PA (4)	407	59	41.0	37.3 (1,3)	55.7	50.7
513708	NA	420	60.9	44.6	40.6 (1,3,4)	78.8	71.7
	PA (4)	410	60.3	53.0	48.2 (1,2,3)	72.3	65.8
513709	NA	419	60.8	55.7	50.7 (1,2,3)	100.2	91.2
	PA (4)	405	58.7	53.3	48.5 (1,2,3)	91.9	83.6
513887	NA	383	55.4	40.7	37.1 (1,3)	81.4	74.0
	PA (5)	436	63.2	59.1	53.8 (1,2,3)	93.1	84.8
513888	NA	403	58.5	45.8	41.6 (1,3)	88.6	80.6
	PA (6)	414	60.0	55.1	50.1 (1,2,3)	95.6	87.0
513889	NA	425	61.6	45.0	40.6 (1,3)	67.4	61.3
	PA(6)	421	61.1	38.1	34.7 (1,3)	54.2	49.3
514041	NA	438	63.5	53.9	100.1	100.1	91.0
	PA(8)	493	71.4	--	--	--	98.6
514042	NA	463	67.2	53.8	49.0 (1,2,3,4	95.2	86.6
	PA(8)	509	73.8	--	52.7	--	77.0
503315	NA	442	64.1	48.7	44.3 (1,3,4)	93.1	84.8
	PA (8)	529	76.8	--	31.6	--	43.3

NOTES:
(1) Invalid due to insufficient specimen thickness
(2) Invalid due to insufficient fatigue precrack length
(3) Invalid due to P(max)/P(o) > 1.10
(4) Aged 12 hours at 464 K (375 F)
(5) Aged 4 hours at 450 K (350 F)
(6) Aged 16 hours at 450 K (350 F)
(7) Stretched 1.5-2.0%
(8) Aged 4 hours at 464 K (375 F)

Table 3. Fracture Toughness of PM 2XXX Al Alloy Extrusions.

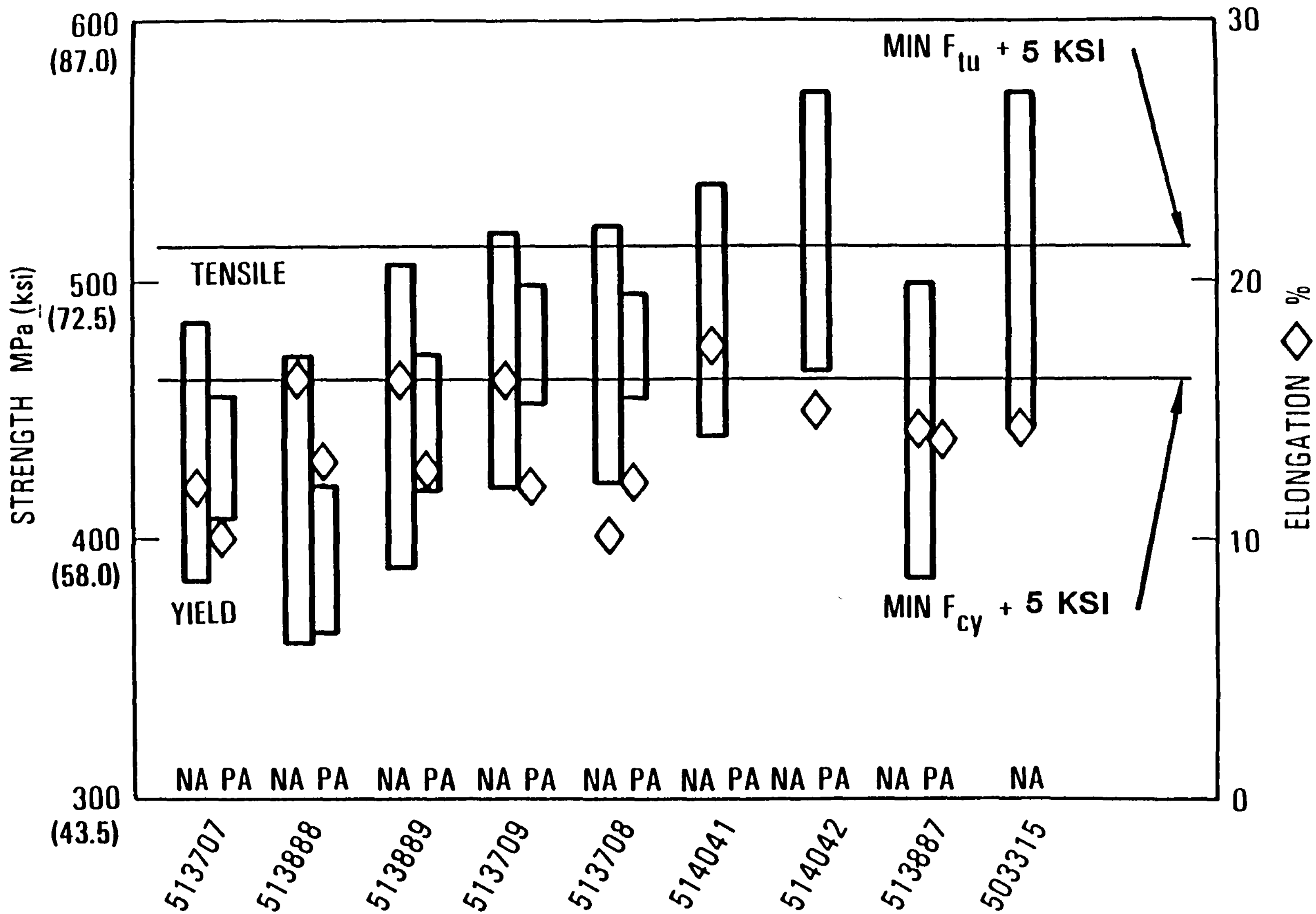


Figure 10. Histograms Showing Performance of PM 2XXX Aluminum Alloys Relative to Strength Requirements for Damage Tolerance and Fatigue Resistance.

The PM composition based on Al-3.70Cu-1.85Mg-0.20Mn with 0.60 wt. pct. Zr was selected for investigation. Flat rolled material consisting of 0.250 in. thick plate and 0.070 in. thick sheet was fabricated using selected thermal mechanical treatments (TMT). The schedule of TMT operations was designed to yield the extreme conditions of grain structure normally encountered in the fabrication of flat rolled products, specifically recrystallized and unrecrystallized. The PM Al alloy plate and sheet materials exhibited improved strength properties at thin gauges compared to IM Al alloys, as a consequence of their enhanced ability to inhibit recrystallization and grain growth. In addition, the PM 2124 Al alloys offer much better combinations of strength and toughness over equivalent IM Al. The alloy microstructures were examined by optical metallography and crystallographic texture techniques in order to establish the metallurgical basis for these significant property improvements.

The prior research on PM 2XXX Al alloys involved the evaluation of Al-Cu-X and Al-Cu-Mg-X alloy compositions in the form of rectangular extruded bar. The PM Al-Cu-Mg-Mn-Zr alloy system exhibited the most attractive combination of properties for damage tolerant and fatigue resistant structural requirements. Since a major usage of 2XXX series Al alloys for damage tolerant structural applications involves the product forms of plate and sheet, it is important to establish the processing methods leading to PM 2XXX Al alloy flat rolled plate and sheet material forms. The technical objectives of the present study address this issue in terms of: (1) exploring the range of potential microstructural variations encountered in the fabrication of flat rolled materials, and (2) establishing the relationships between deformation processing conditions, alloy microstructures, and mechanical property behavior.

Conclusions - Fourth Iteration Development Studies (6)

The development study on PM 2XXX Al alloy plate and sheet materials has demonstrated the following:

- PM 2XXX Al alloys can be produced in plate and sheet material forms with outstanding strength and fracture toughness improvements over IM Al alloys.
- PM 2XXX Al alloys show a significant advantage in yield strength properties compared to equivalent IM Al alloys in thin plate and sheet gauges (Figure 11).
- Due to the presence of both Al_3Zr and oxide phases, the PM Al alloy materials are unusually more resistant to recrystallization processes (or concomitantly, a greater insensitivity to variations in processing history) than IM Al alloys.
- Although recrystallization does occur in thinner gauges of some PM Al alloy materials, aging treatments are effective in providing attractive property behavior.

2.5 Fifth Iteration Development Studies

The goal of this study was to develop high strength and modulus SiC whisker reinforced aluminum MMC's for selected supersonic airframe structural applications.(3,7) The materials processing feasibility of producing 2124, 2124-Zr modified, and 2219 Metal Matrix Composite (MMC) extrusions with 15 and 25 weight percent SiC was demonstrated early in the program. Three MMC systems exhibited a 30 percent improvement in tensile strengths and a 50 percent elastic modulus improvement compared with unreinforced aluminum alloys. The 2124 and 2124-Zr modified aluminum alloy MMC showed higher strengths than the 2219 MMC. In addition, the 2124 MMC strains-to-failure values of 2-4 percent were generally higher. The naturally aged heat treatment (-T4 temper) displayed a superior combination of tensile strength, elastic modulus, and ductility properties for both the 2124 and 2219.

Elevated temperature behavior and other mechanical property testing of the 2124 and 2219 MMC extrusions was also completed. The elevated temperature and stability properties at 250^{o} and 350^{o}F exceeded target requirements for both short and long time exposures. Notched tensile test results were below the trend line of ingot metallurgy (IM) aluminum alloys.

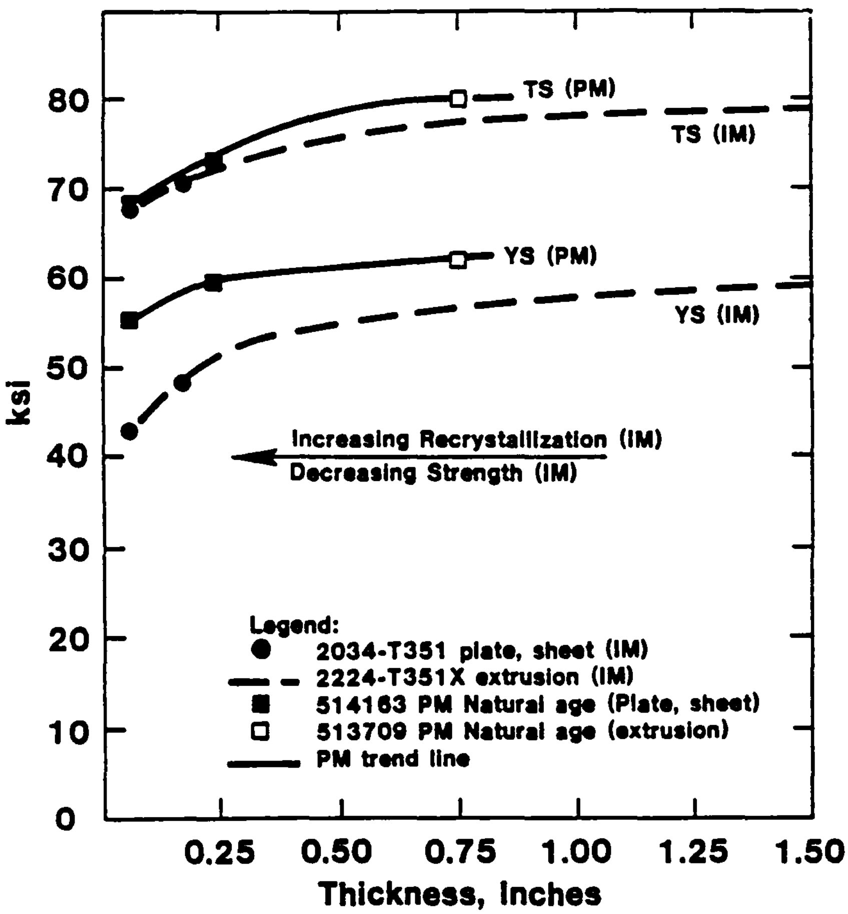


Figure 11. Comparison of Tensile and Yield Strength Variation With Product Thickness of PM 2XXX and IM 2XXX Al Alloys.

Microstructural analyses showed that the low notched tensile values were associated with solidification dendrites and foreign particle inclusions. The un-notched fatigue strength of the 2219 15 weight percent MMC was approximately 25 pct. higher than the baseline aluminum alloy.

Improvements in mechanical properties were demonstrated for the 2219 MMC through refinements in processing technology and optimization of alloy chemistry. The Zr modified 2124/15 weight percent MMC was selected for initial chemistry variation studies because of its aforementioned strength, stiffness, ductility, and stability performance. The grain refinement and dispersion hardening advantages ascribed to Zr was a factor in the selection as well as the desirability of focussing program resources on the most promising single system. Demonstration of gains in ductility and toughness without sacrifices of strength, stiffness, and stability attributes was an expectation of the current work.

MMC Goals

- o 2124, 2124-Zr modified, and 2219 aluminum alloys were selected for reinforcement with SiC. This matrix alloy selection was primarily based on their room temperature property behavior. The 2124 aluminum matrix system represents a moderate strength, high fracture toughness alloy, and 2219 aluminum matrix represents a moderate strength, elevated temperature resistant alloy.

- o Room temperature and short time elevated temperature, 250^{o} and 350^{o}F, tensile strengths exceed the target strengths established for the high strength, high modulus material. Tensile elongation remains below the 5 pct. target goal.

- o Room temperature tensile strength after exposure for 100 to 336 hr. at 250^{o} and 350^{o}F were below tensile strength levels obtained without thermal exposure.

- SiC reinforced 2219 aluminum alloy exceeded the fatigue strength and life target goal.

- Differences between 0.5 x 5.0 in. cross-section extruded bar and approximately 0.75 in. extruded rod materials were determined in terms of mechanical properties and microstructures. Composites based on standard 2124 and 2124-Zr modified compositions were produced and evaluated in the present effort.

- A systematic investigation of the influence of thermal mechanical treatment on tensile properties was undertaken on the 2124 Al/15 wt. pct. SiC whisker extruded bar. The solution treatment and isothermal aging temperatures and times were optimized with respect to target objectives.

- An improvement in MMC billet processing was implemented and verified by appropriate chemical and mechanical property evaluations. It has been demonstrated that reduced solute content losses and SiC whisker quality levels have been instrumental in accounting for these billet improvements.

Improvement in elevated temperature stability properties will require an Al/SiC MMC material with a more temperature resistant matrix. The 2124 and 2219 Al/SiC MMC alloys as developed have very favorable properties for sub-sonic aircraft. The 2124-Zr modified Al alloy being evaluated in this study may offer the required improvement in thermal stability.

This report covers a development effort exploring Al powder metallurgy-discontinuous SiC composite materials. These metal matrix composite materials are of interest for higher performance commercial aircraft because of their relatively low cost, ease of fabrication, and potential strength and stiffness payoffs. Target properties for this class of materials are shown in Table 1. The detailed objectives of the development effort include:

- o Determine the effect of alloy modification to standard 2124 Al alloy matrix on overall property behavior of Al/SiC composite materials.

- o Assess potential for improvement in strain-to-failure or ductility values for Al/SiC materials by employing selected heat treatment conditions

- o Determine mechanical and physical properties, and thermal stability of MMC Al/SiC

Theoretical Background

Composite materials consist of individual phases that are bonded together in such a manner that the average properties of the composite are determined by the individual properties of each phase. Generally, the composite is constructed in order to gain advantageous characteristics from each of the component materials or to overcome disadvantageous characteristics. Alloy materials containing small amounts of finely dispersed second phase particles are normally not considered composites because the dispersed phase affects properties by interacting with the primary phase, rather than by contributing on its own. The term composite usually refers to materials in which the volume fraction of the minor phase is at least 10 or 15 pct.

Fiber reinforcement of composite materials occurs when thin fibers are oriented in a ductile matrix. The bulk properties of composites in terms of the individual components can be approximated by considering four stages in the stress-strain behavior of fiber reinforced composites:(8)

1) elastic deformation of fibers and matrix occurs until just beyond normal elastic limit of matrix phase
2) matrix continues to deform plastically while fibers still deform elastically
3) plastic deformation of both fibers and matrix
4) fracture of fibers followed by total fracture of specimen

Of the four stages, Stages 1 and 2 are the most significant from an engineering viewpoint since they account for a large portion of the stress-strain curve. The tensile loading of a unidirectional continuous filament composite material in Stage 1 of stress-strain behavior is illustrated schematically in Figure 12. If the fibers and matrix are well bonded together, such that the strain (e) in each interface is the same (isostrain), then the elastic stresses in the composite will vary according to the modulus of the fiber and matrix, respectively. The total stress is given by the sum of the loads carried by each phase

$$\begin{aligned} \sigma_c &= \sigma_f\, v_f + \sigma_m\, v_m \\ &= E_f\, \epsilon v_f + E_m\, \epsilon v_m \\ \sigma_c &= E_f\, \epsilon v_f + E_m\, \epsilon(1-v_f) \end{aligned} \tag{1}$$

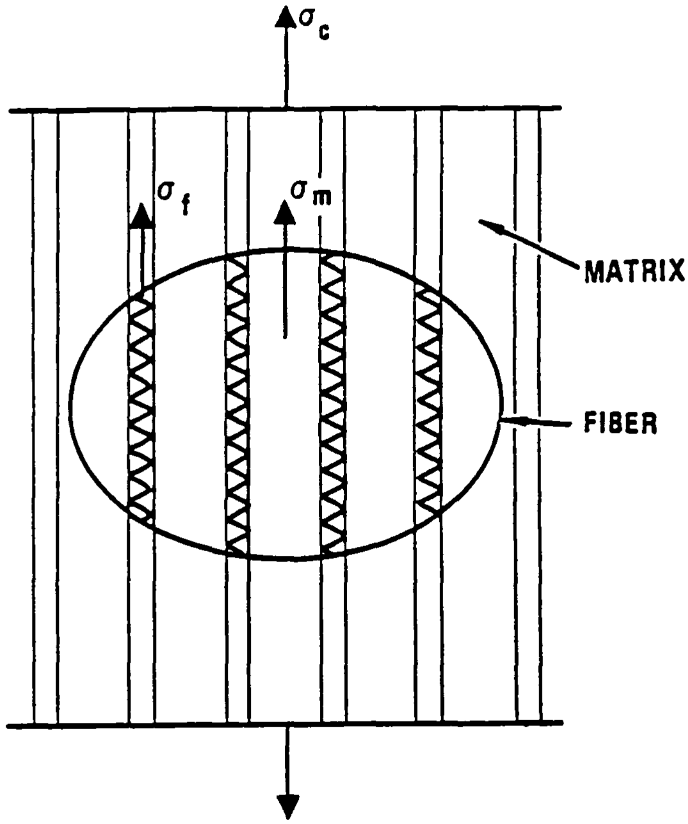
so that the composite modulus $E_c = \sigma_c/\epsilon$ is given by

$$E_c = E_f v_f + E_m\,(1-v_f). \tag{2}$$

Thus, Equations (1) and (2) describe the tensile strength and elastic modulus of a fiber reinforced composite material in terms of the individual properties of its components. σ_c and E_c of the composite are observed to be linearly related to the volume fraction of fiber reinforcements. To realize a benefit from the presence of the fibers, the strength of the composite material must be greater than the tensile strength of the matrix (σ_u), so that

$$\sigma_c = \sigma_f v_f + \sigma_m\,(1-v_f) > \sigma_u \tag{3}$$

The strengthening of composites by fiber reinforcements depends critically upon the successful transfer of load from the ductile matrix to the strong fibers. If the fibers are not continuous, then the fibers and matrix are not strained the same amount and Equation (1) no longer applies.



ASSUMPTIONS: – LOAD APPLIED PARALLEL TO FIBER REINFORCEMENTS
– ELASTIC STRAIN IDENTICAL IN MATRIX AND FIBER

NOTATION: σ_c, σ_f, AND σ_m – TENSILE STRESS PRESENT IN COMPOSITE, FIBER, AND MATRIX RESPECTIVELY

ϵ_c, ϵ_f, AND ϵ_m – TENSILE STRAIN PRESENT IN COMPOSITE, FIBER, AND MATRIX RESPECTIVELY

E_f AND E_m – ELASTIC MODULUS OF FIBER AND MATRIX RESPECTIVELY

V_f AND V_m – VOLUME FRACTION OF FIBER AND MATRIX RESPECTIVELY

Figure 12. Schematic Illustration of Stress-Strain Behavior During Tensile Loading of Composite Material With Continuous Fiber Reinforcement.

To determine the efficiency of the discontinuous fiber in strengthening the composite it is necessary to calculate the extent to which the load is transferred to the fibers. By assuming a linear distribution of tensile stress in the fiber with fiber length and integrating over the volume fraction of reinforcements, it is possible to derive the following strengthening relationship.(8)

$$\sigma_c = \sigma_f v_f \, [(1-(1-\beta))/(1/l_c)] + \sigma_m \, (1-v_f) \qquad (4)$$

where l is the discontinuous fiber length, l_c is the critical fiber length, and b is a property constant equal to approximately 0.5. For $l/l_c = 10$, the strength of the discontinuous fiber composite is calculated to be 95 pct. of the continuous fiber system. With fiber composites of engineering interest, l_c is about 5 times the fiber diameter, thus requiring a length-to-diameter of about 50 to ensure maximum strengthening in the composite material. By way of summary, for the greatest strengthening with fiber reinforcements, the fibers should have a high elastic modulus to achieve high strength at low strains and a high tensile strength. Ideally, the fibers should occupy as large a volume fraction as possible, and they should be perfectly aligned in one direction without discontinuities.

Composite strengthening with fiber reinforcements is one of two fundamentally different approaches aimed at achieving high strength in materials. The alternative approach is based on limiting the motion of dislocations. Strengthening methods have been discussed extensively in connection with solution and particle hardening and generally involve immobilizing the matrix dislocations with finely spaced barriers. The principle of fiber reinforcement does not rely primarily on restricting plastic flow, but uses plastic deformation in the matrix to load the oriented fibers. Recent technologies have produced a variety of fibers with very high strength and modulus. The fibers cannot be used directly because of their small size, and the fact that they are generally brittle and fracture with little or no plastic deformation (low fracture toughness).

However, if the discontinuous fibers are combined with a tough, ductile matrix, then a useful engineering material can result with both high strength and toughness.

Fiber composites can even maintain high strengths at elevated temperatures where the matrix strength decreases appreciably, provided three conditions are met.(9) First, the fibers must be long enough to ensure that they are appreciably loaded. For example, if the matrix strength decreases by a factor of 10 with increasing temperature, then l_c increases by a similar factor of 10. Secondly, the fracture strength of the fiber must not change appreciably in the temperature range of interest. This condition is easily fulfilled by many high melting temperature fibers such as Al_2O_3 and SiC. And lastly, the fiber-matrix system must be chemically stable at elevated temperatures. That is, the fiber must not be degraded by chemical attack, diffusion, alloy formation, or any other interaction with the matrix. Since the Al alloy matrix and SiC reinforcement meet these three requirements, the prospect of high performance MMC materials represents a logical extension of the current development effort.

Conclusions - Fifth Iteration Development Studies

- The incorporation of SiC whisker reinforcements in 2124 Std and 2124-Zr modified Al alloy matrices was demonstrated from a materials processing viewpoint in which 0.5 in. x 5.0 in. cross-section extruded bars were fabricated. It was shown that refinements in the composite billet processing lead to significant improvements in the solute content of the Al alloy matrix.

- Extruded SiC reinforced composites based on 2124 Std and 2124-Zr modified Al alloy compositions exhibited improvements in tensile strength of 25 pct. and in elastic modulus of 45 pct. compared with conventional Al alloys.

Tensile properties of these Al/SiC composite materials were shown to surpass the target objectives that include a combination of high strength and high modulus. The 2124 Std Al alloy matrix exhibited slightly higher strength with SiC whisker reinforcements than the 2124-Zr modified Al alloy system.

- o Tensile elongations of total strain-to-fracture values remained below the 5 pct. target objective. However, substantial improvements in ϵ values were observed for both Al/SiC composite systems, and those were generally attributed to homogenization of solidification defects by using modified SHT schedules. Artificially aged -T6X and -T8X tempers displayed 2 to 3 pct. values of e_f, which represents an improvement of nearly 250 pct. compared to previous studies.

- o For both 2124 Std and 2124-Zr modified Al MMC/SiC whisker systems, an artificially aged heat treatment temper (obtained by 375^{o}F aging) exhibited an optimum combination of tensile strength, elastic modulus, and ductility properties with respect to program objectives (Figures 13 and 14).

- o Homogenization of the 2124 Al/SiC whisker composites by using high temperature soaking treatments was primarily responsible for the overall improvement in property Behavior. An optimization of the SHT schedules was conducted in the -T4 temper for each of the Al/SiC whisker composite materials.

- o The presence of Al_3Zr dispersoid phases in the 2124-Zr modified Al/SiC whisker composite materials is suggested to cause an alteration of the precipitation hardening sequence normally associated with Al-Cu-Mg alloys.
  For this reason, the under-aged -T6X conditions in this alloy system seem to offer a unique combination of tensile strength and ductility.

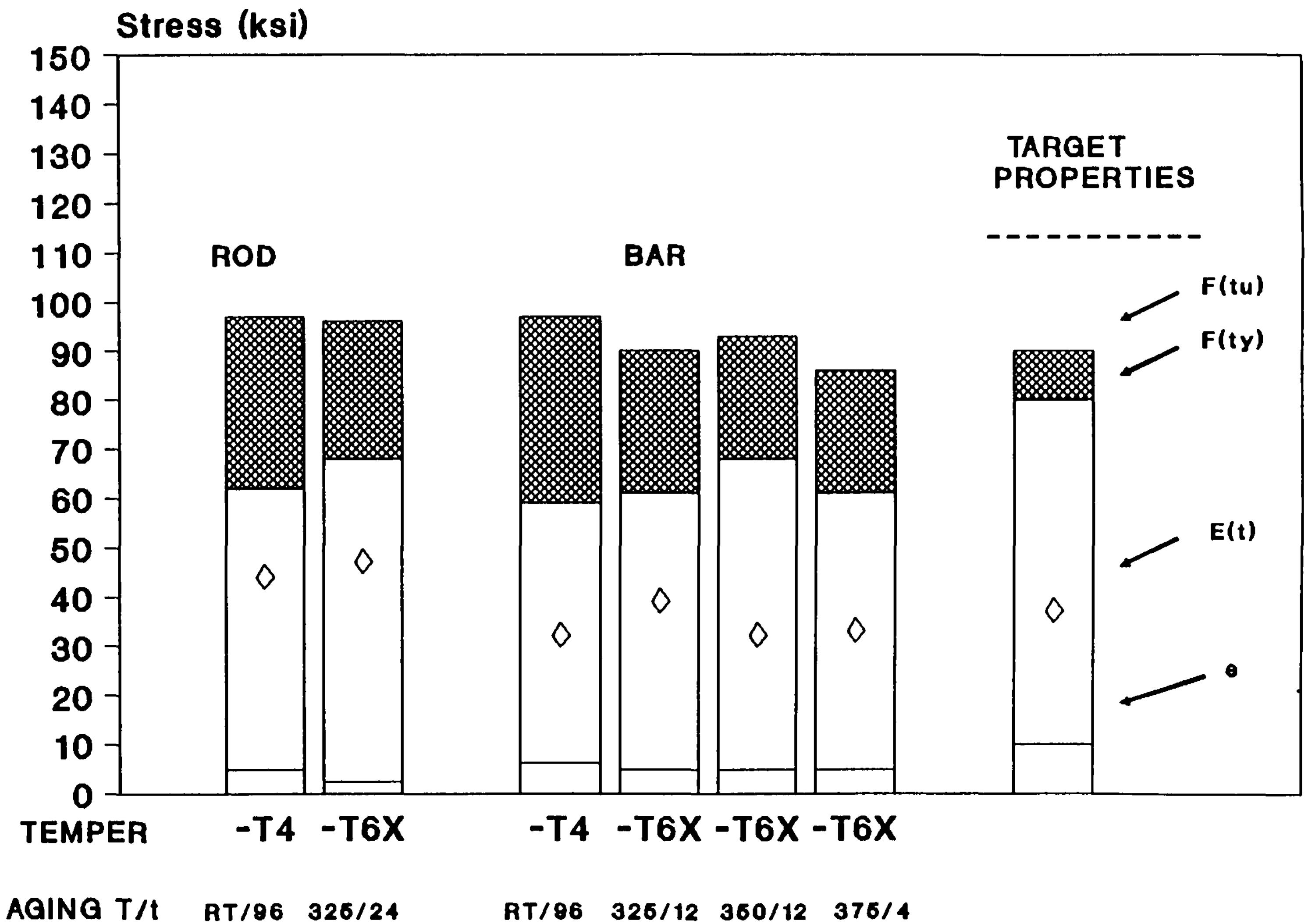


Figure 13. Effect of -T6X Peak-Aged Tempers on Tensile Properties of 2124 Standard Al/15 wt. pct. SiC Whisker Extrusions.

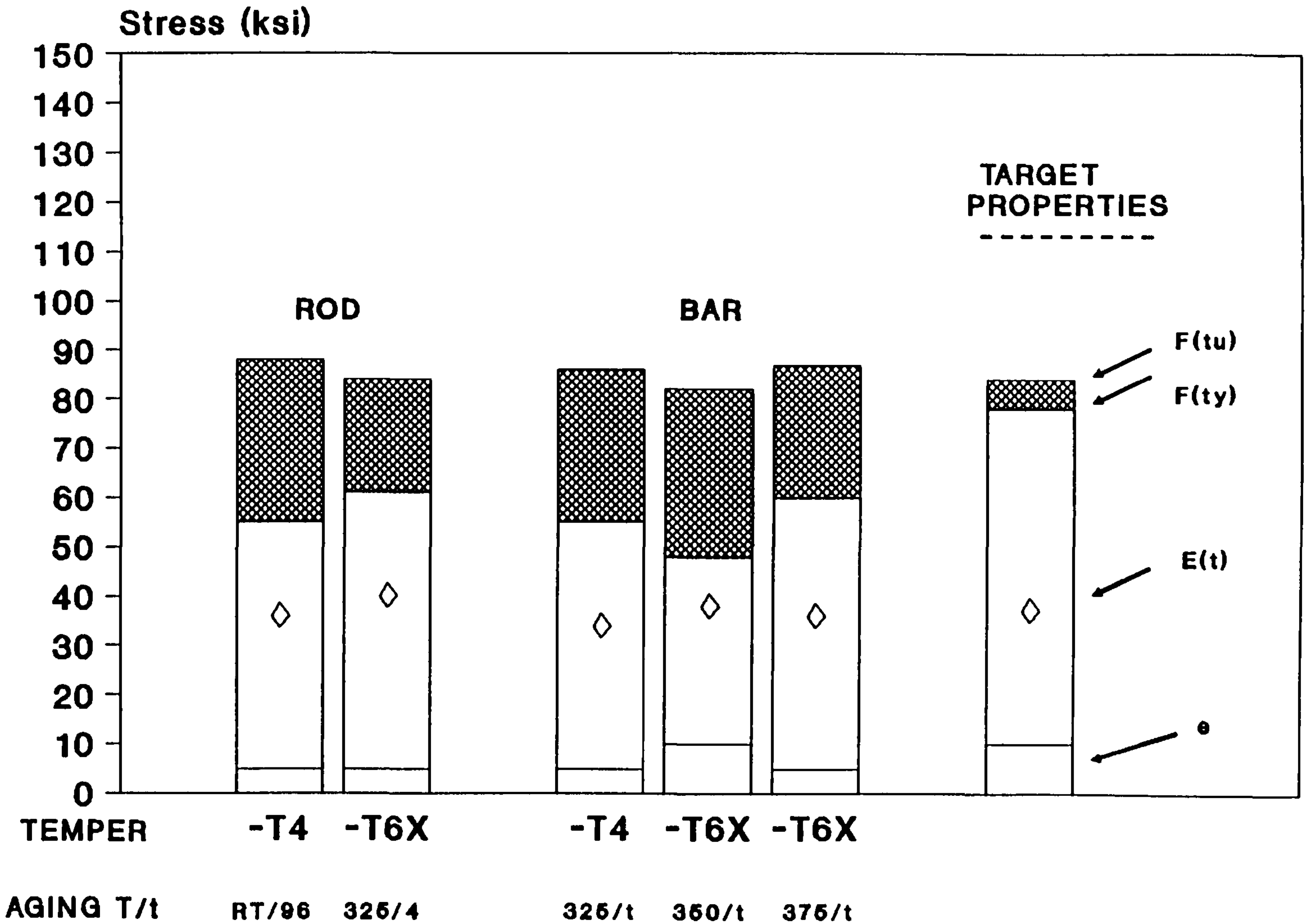


Figure 14. Effect of -T6X Under-Aged Tempers on Tensile Properties of 2124-Zr Modified Al/15 wt. pct. SiC Whisker Extrusions.

3.0 OVERVIEW OF RECENT DEVELOPMENT STUDIES (SEPTEMBER 1985 - August 1991)

3.1 Introduction

The introduction and structural application of powder metallurgy (PM) and metal matrix composites (MMC) 2XXX series Al alloys in aircraft components is currently limited by the lack of an established engineering property database. Flat rolled sheet and plate, and shaped extrusions, represent the major product forms of interest, since these products are designed primarily for damage tolerant and fatigue resistant applications. The technical objectives of the follow-on study are: 1) determining the property variations in fabricated sheet, plate, and extrusion, and 2) establishing the relationships between mechanical property behavior, alloy microstructure, and deformation processing conditions. Lockheed Aeronautical Systems Co. and two (2) Al suppliers investigated the fabrication and characterization of flat rolled and extruded products. In Task I we investigated a candidate PM 2XXX Al alloy, and we investigated a MMC 2XXX Al alloy matrix reinforced with SiC and B_4C in Task 2. A brief description of the fabrication and evaluation efforts by each Al producer is given in the following sections.

3.2 Background

One PM 2124 Al alloy composition with Zr modifications was selected for study in Task 1. It was demonstrated that the Al-Cu-Mg-X type (2124 Al) with 0.70 wt. pct. Zr addition offers a significant improvement over both alternative PM alloys and IM equivalent compositions.

The target aluminum composition of

Al-3.70Cu-1.95Mg-0.20Mn-0.70Zr

was selected for the Task 1 PM alloy and the Task 2 MMC alloy. Lockheed, Alcoa, and NASA technical representatives concurred with this selection.

The same nominal 2124 Al alloy composition with 15 weight percent SiC whisker and B_4C particulate was selected for study in Task 2. The major portion of the technical effort undertaken by Advanced Composite Materials Corp. (ACMC) involved the procurement and processing of constituent materials for SiC or B_4C reinforced MMC extrusions. However, Valimet did produce the fine alloy Al-Cu-Mg-Zr powder in the -325 mesh (< 45 micron) size range for ACMC.

3.3 Approach

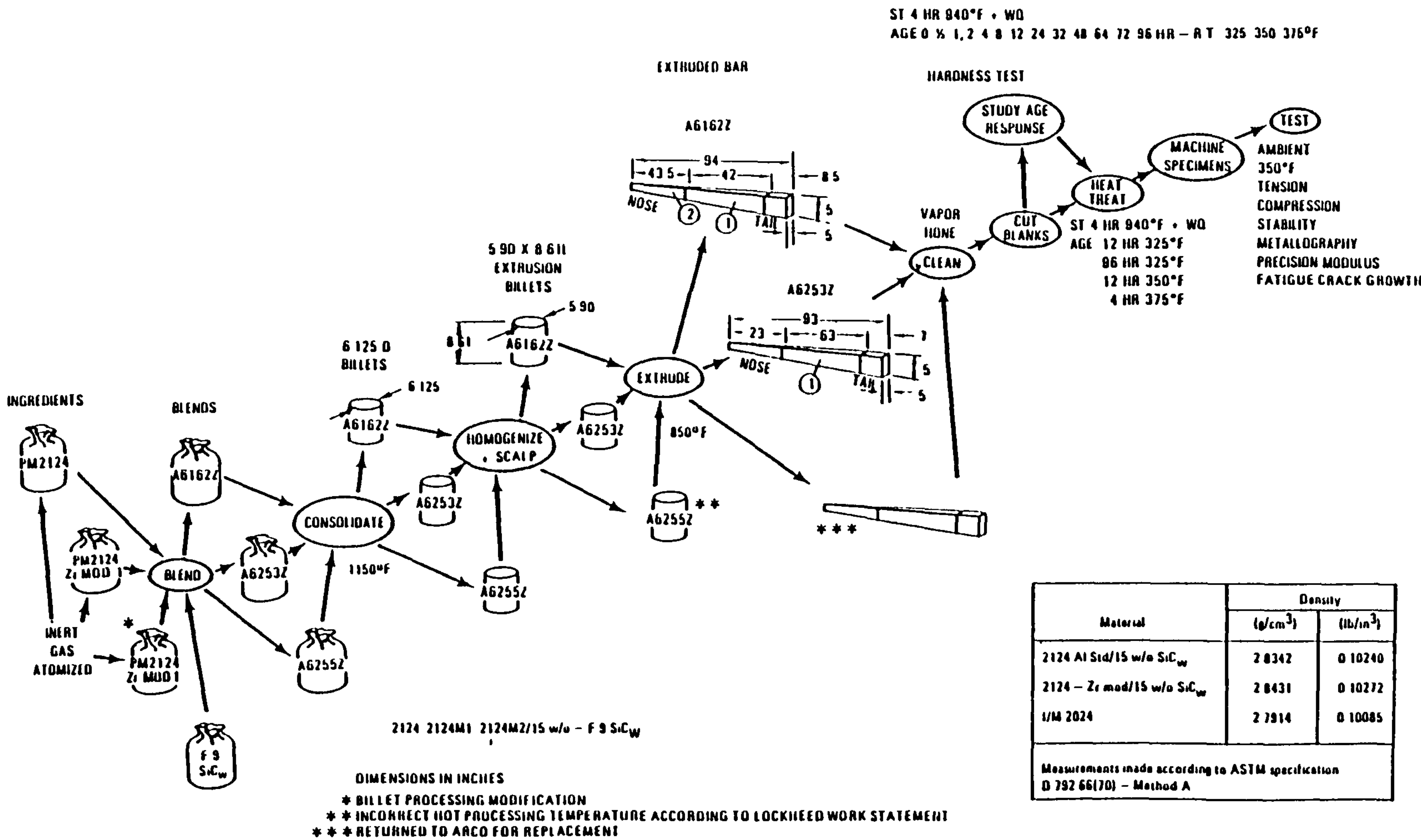
Powder Metallurgy - Task 1

A remnant PM forged slab (2 in. x 10 in. x 18 in.) available from the previous Al alloy development program was fabricated into flat rolled gauge materials for initial property characterizations. The target composition of the remnant slab was identical to the chemistry and Cu/Mg solute ratio shown above. The rolling schedule strategy was designed to provide plate and sheet representative of the extreme differences encountered in rolled product microstructures, namely: (1) fully recrystallized grain structure, with a random texture, and (2) unrecrystallized grain structure respectively. Pre-aging and warm rolling (plate -WR) was employed to yield a predominantly recrystallized grain structure morphology. Hot rolling (sheet - HR) at temperatures below the solvus were used to maintain a primarily unrecrystallized grain structure. The PM slab was initially cross-rolled in one pass to a width of approximately 12 in. and then cut in half length-wise for rolling to plate and sheet materials.

The slab (designated 514163-WR) was pre-aged at 750°F for 12 hr. and air cooled to room temperature. Subsequently, it was re-heated to 500°F and warm rolled to 0.255 in. thickness plate. The slab (designated 514163-HR) was heated to 920°F and soaked for 2 hr. It was removed from the furnace and allowed to cool to approximately 875°F, where it was subsequently hot rolled to 0.080 in. thickness in five passes. The hot rolled slab was then re-heated to 875°F and hot rolled to 0.077 in. thickness using large reductions per pass. The two rolled products were solution heat treated at 935°F for 1 hr., cold water quenched, stretched 2.0-3.0 percent, and artificially aged at 350°F for 16 hr. to a -T8X temper. Some evidence of foreign particle inclusions was observed in the original powder lots, although little influence was noted on overall property behavior. The test matrix for each flat rolled material variant included tension, compression, and fracture toughness coupons.

Metal Matrix Composites - Task 2

The alloy powder for Task 2 was inert gas atomized, screened, and shipped to ACMC for subsequent processing. A schematic diagram of the fabrication procedures used for the MMC is shown in Figure 15. The SiC whisker and B_4C particulate reinforcements were weighed and mixed by ACMC with the atomized metal powder to achieve 15 weight percent reinforcement. ACMC's proprietary wet mechanical mixing process was used to obtain a uniform blend. The metal powder/SiC and B_4C mixtures were consolidated according to the following sequence: 1) the mixture was loaded into a vacuum hot press with graphite coated dies, 2) cold compacted at 20 ksi, 3) evacuated at room temperature to a pressure of less than 50 micron, 4) the compact was vacuum degassed by slowly raising the furnace temperature up to 750° F while maintaining a vacuum of less than 50 micron, 5) hot consolidated in a partially liquid phase (1100° to 1150°F) region to obtain a fully dense billet. Hot consolidation at a temperature slightly above the alloy solidus is required to produce a high density billet and to encourage adhesion between the aluminum alloy matrix and SiC and B_4C reinforcements.



Material	Density (g/cm^3)	Density (lb/in^3)
2124 Al Std/15 w/o SiC$_w$	2.8342	0.10240
2124 – Zr mod/15 w/o SiC$_w$	2.8431	0.10272
I/M 2024	2.7914	0.10085

Measurements made according to ASTM specification D 792 66(70) – Method A

Figure 15. Schematic Diagram of Processing Sequence for MMC 2124 Al/SiC Whisker Materials.

The resulting hot consolidated billets were machined to a nominal size of 6.0 in. diameter x 8.5 in. length. The three composite billets were extruded to 0.5 in. x 5.0 in. rectangular bar and furnished to Lockheed in the -F temper. A streamline extrusion die was employed to promote steady-state flow and eliminate surface tearing. Both the MMC billets and the extrusion dies were coated with commercial $MoSi_2$ lubricant to facilitate lower break-out pressures around 35 ksi.

3.4 Progress on PM 2XXX Al Alloy Products

An initial property evaluation of the PM 2124 mill products was performed and results were compared. Tension and compression strengths, tensile ductility, fracture toughness, and bearing properties for the plate and sheet are shown in Figures 16 and 17, respectively. Target property goals are also indicated on the plots for purposes of comparison. Tensile strength levels for both plate and sheet (514163-WR and -HR, respectively) were somewhat higher than reported in the previous contract effort. Differences in property behavior are probably due to minor alterations in the thermal mechanical processing (TMP) conditions employed in the fabrication of the warm and hot rolled materials. The tension and compression yield strengths are similar for the PM 2124 Al alloys (within 1-2 ksi), which suggests that the Bauschinger effect has a negligible influence on hardening. Moreover, both the tension and compression strength levels for the PM Al alloy materials in the -T8X temper exceeded target objectives by 2-5 ksi. The lower ductility values observed in the PM 2124 Al sheet are currently unexplained, but are probably a consequence of mixed grain structures. Metallographic and texture measurements indicated that the warm rolled variant (-WR) contained components of partial recrystallization.

The recrystallized grain structure consisted of a pattern of elongated grains approximately 50 micron in diameter, interspersed with original unrecrystallized grains similar to extruded products.

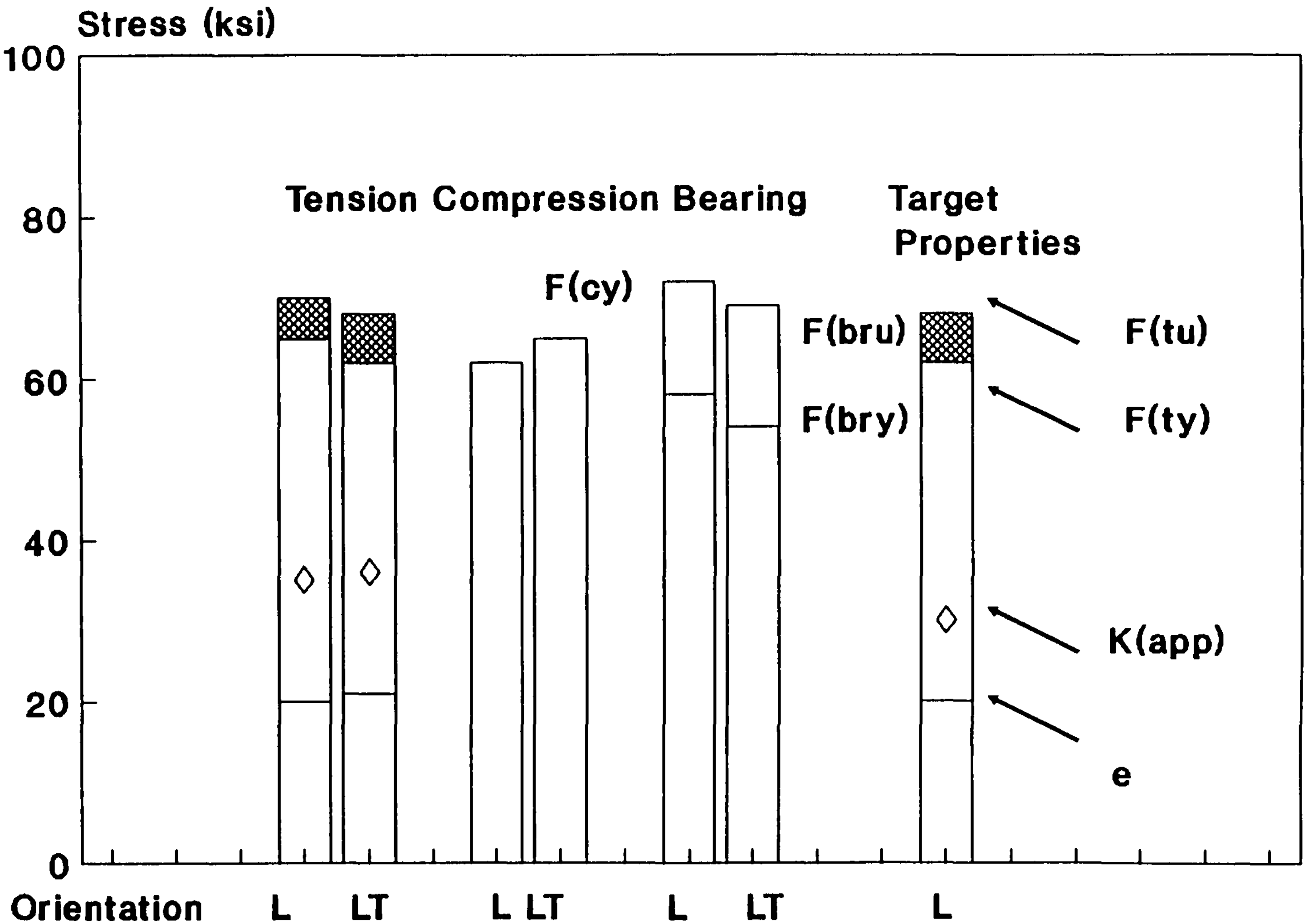


Figure 16. Mechanical Properties of Warm Rolled Plate Variant (S. No. 514163 - WR), -T8X Temper (350°F/16 hr.).

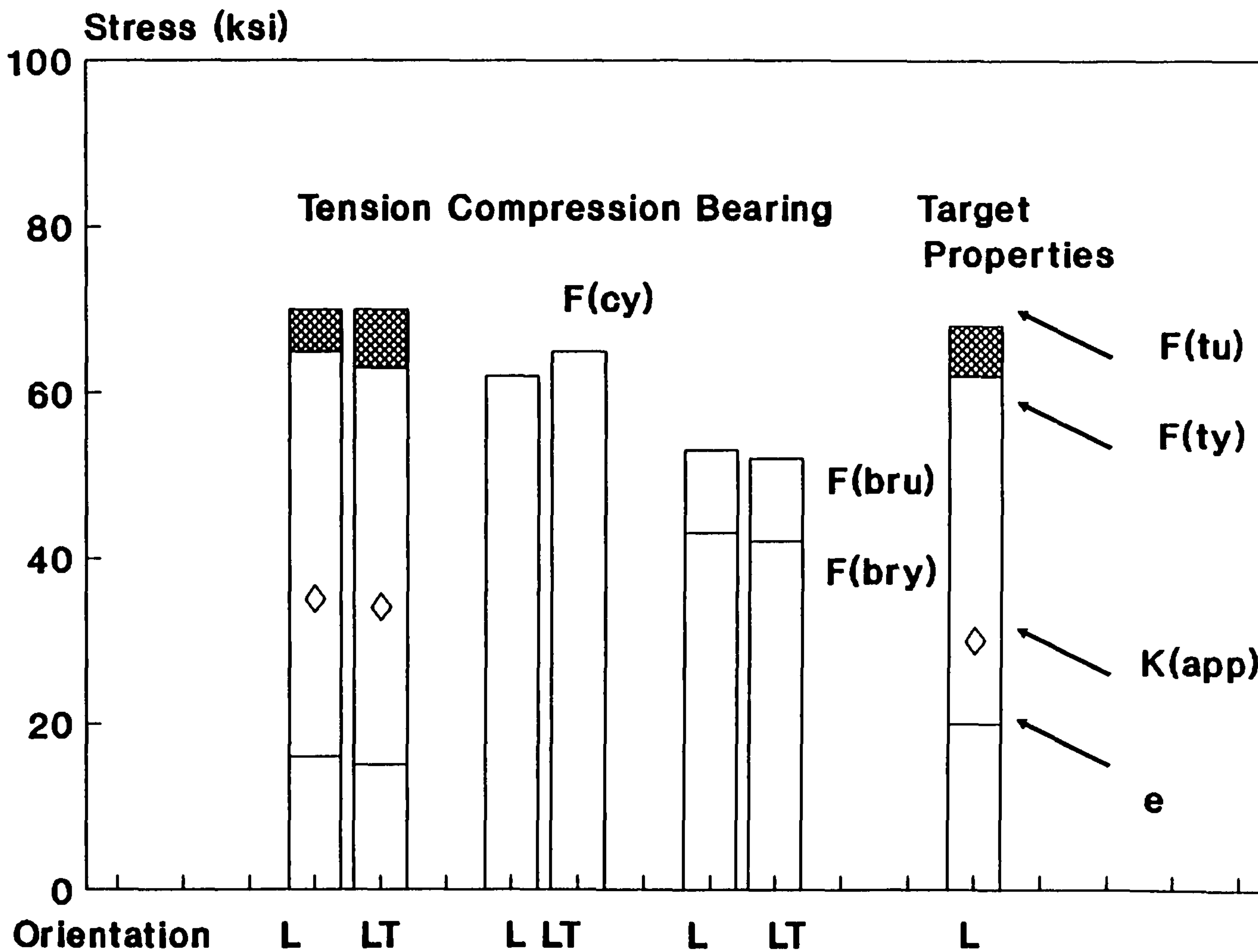


Figure 17. Mechanical Properties of Hot Rolled Sheet Variant (S. No. 514163-HR), -T8X Temper (350^{O}F/16 hr.).

The warm rolling schedule was only partially successful in generating an alternative microstructure in the PM 2XXX Al alloys, due to the potent influence of Zr in inhibiting recrystallization tendencies. Hot rolled products generated a more elongated grain structure than observed in similar extruded shapes.

Fracture toughness levels in terms of K_{app} measurements also exceeded target goals, in all cases by at least 10 ksi-in.$^{1/2}$. These toughness results are particularly significant since relatively narrow center-crack-tension (CCT) panel specimens were used in the test evaluations (Table 4). Improvements of 15-25 pct. in K_{app} values are typically found in high strength Al alloys at panel widths of 12-16 in. Isotropic tension, compression, toughness, and bearing properties were observed in the PM 2124 products, as opposed to the significant directional influences often associated with conventional wrought IM alloys. Apparently, the PM alloys are associated with a more uniform deformation behavior in the elastic and plastic regions.

The S-N notched fatigue behavior of the candidate PM 2XXX Al (plate-WR and sheet-HR) was evaluated in axial, constant amplitude notched fatigue tests. An R ratio of +0.1 was used with a notch concentration factor of K_t = 3.0. The notched fatigue results for the plate and the sheet are given in Figure 18 for the artificially aged -T8X temper. A standard high strength Al alloy fatigue curve is also drawn on the figure for purposes of comparison. The fatigue resistance of the PM 2XXX Al sheet and plate is marginally superior to the IM baseline, particularly in the LCF region.

Preliminary fatigue crack growth rates for the PM Al alloy sheet were determined and compared with the target objective in Figure 19. The test conditions consisted of constant amplitude loading, an R ratio of +0.10, a frequency of 25 Hz, and laboratory air with a relative humidity of 95 percent. Crack growth rates were generally observed to be lower in the mid da/dn - K region for both specimen orientations.

Specimen Number	F_{ty} (ksi)	Orientation	Panel Width (in.)	K_{App} (ksi - sq. rt. in.)
KSPM-1	65.3	L-T	3.0	72.4
KSPM-2	66.4	L-T	3.0	69.6
KSPM-1A	65.8	L-T	6.0	76.8
KSPM-2A	66.0	L-T	6.0	73.7
KSPM-3A	64.7	L-T	6.0	(1)
KSPM-4A	65.2	L-T	6.0	74.0
KSPM-3	63.3	L-T	2.5	66.4
KSPM-4	64.1	L-T	2.5	68.9

NOTE: (1) Failed During Pre-Cracking

Table 4. Preliminary Compact Tension Toughness Properties for PM 2124 Sheet (S. No. 514163-HR), -T8X Temper (350°F/16 hr.).

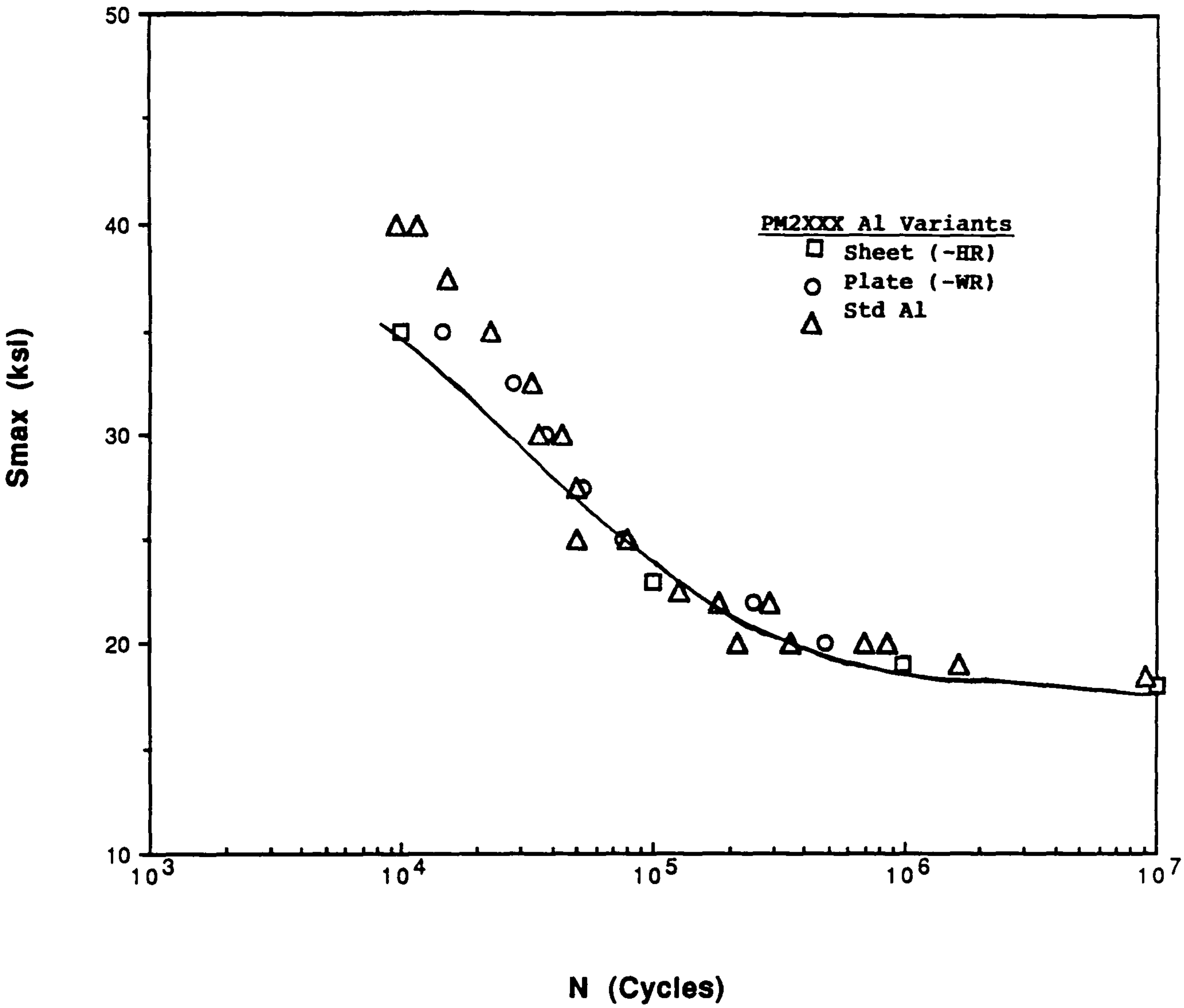


Figure 18. S-N Notched Fatigue Properties of PM 2XXX Al Sheet and Plate (S. No. 514163), -T8X Temper (350°F/16 hr.).

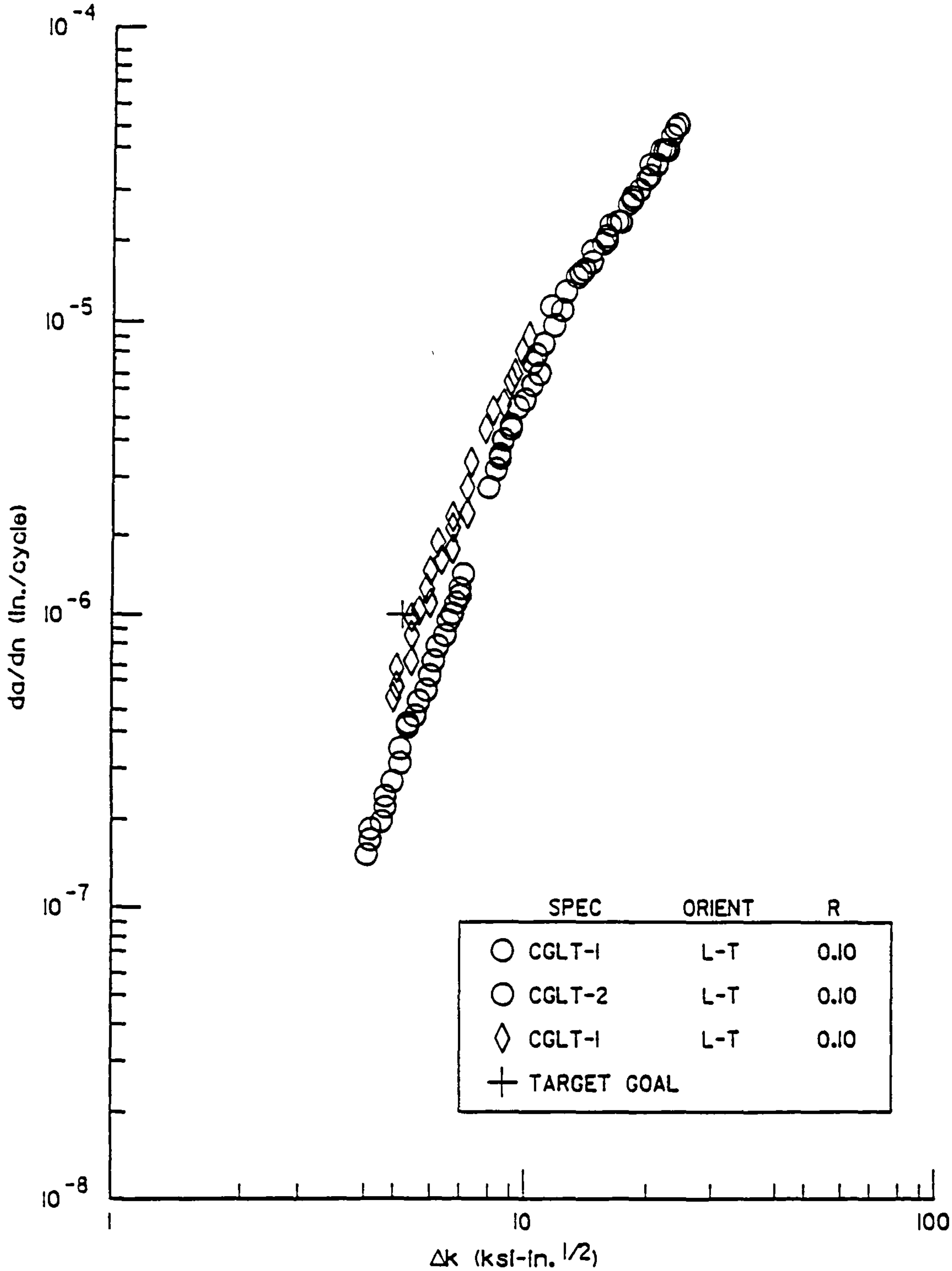


Figure 19. Fatigue Crack Growth Rate Behavior of PM 2XXX Al Sheet (S. No. 514163-HR), -T8X Temper.

These PM 2XXX Al test results are consistent with other findings on PM Al alloy products. Based on these combinations of strength, toughness, and fatigue initiation and propagation properties, the PM 2124 Al alloy plate and sheet materials are certainly consistent with the requirements for superior damage tolerance. The use of PM processing leads to significant advantages in mechanical fatigue and crack growth properties over conventional IM 2XXX Al alloys.

3.5 Progress on MMC Products

Control samples were cut from the as-received bars and heat treated to either a -T3X or -T8X temper using the modified solution heat treatment of ST 940^{o}F for 4 hr., followed by a cold water quench. A nominal amount of cold work was introduced by stretching the samples 0.8-1.2 percent prior to aging. Isothermal aging curves for the MMC 2124 Al alloy extrusions were obtained using hardness and conductivity measurements. Typical age hardening responses are shown in Figure 20 for both the SiC and B_4C reinforced bars, as well as the PM 2124 baseline. Peak hardness levels for the 2124 MMC extrusions were similar, although the aging kinetics exhibited significant differences in behavior. Candidate heat treatment conditions at 350^{o}F were selected based on the hardness response curves. The initial tensile property results for the 2124 SiC and B_4C MMC extrusions were compared with target objectives. Tensile property results as a function of aging conditions are shown in Figure 21. The strength and elastic modulus levels for the SiC reinforced extrusions in both the -T3X and -T8X tempers exceeded the B_4C properties. However, the properties of the B_4C extrusion were more isotropic in behavior due to the presence of particulate reinforcements instead of aligned SiC whisker reinforcements. Overall strength levels are comparable with target goals, and exhibit approximately 10-15 percent improvements through stretching prior to aging (-T8X temper).

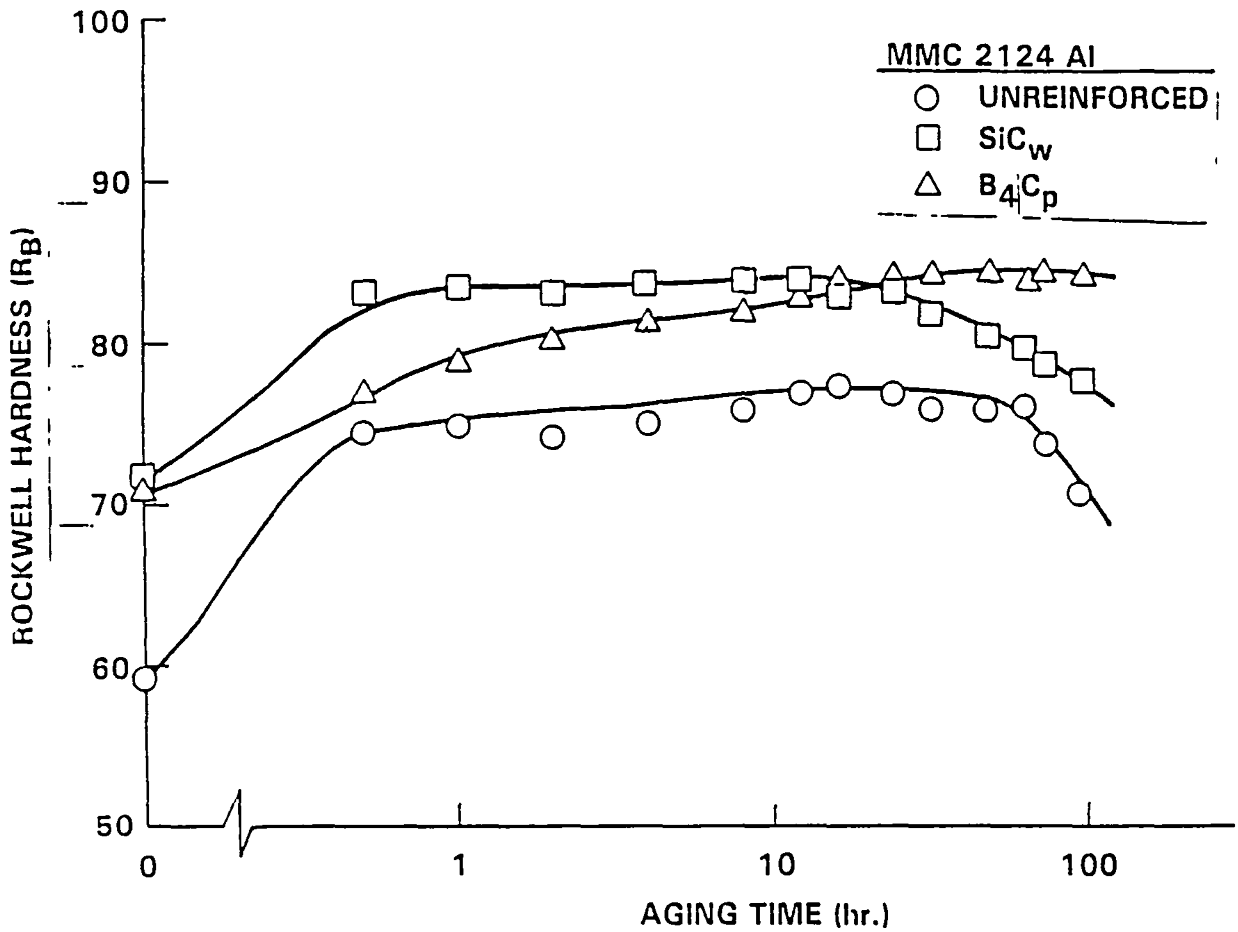


Figure 20. Age Hardening Response of MMC 2124 Al Alloy Extrusions at 350°F.

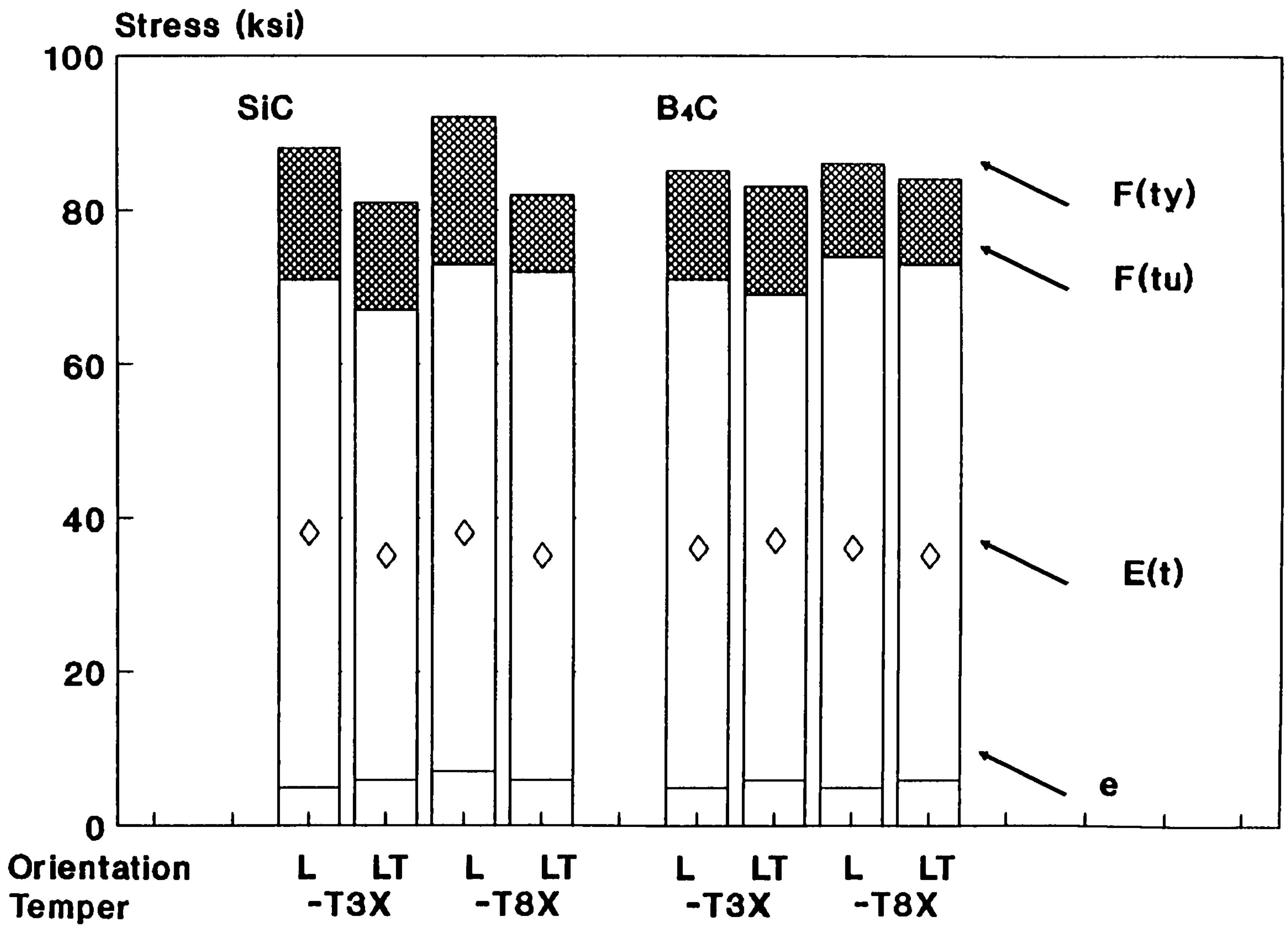


Figure 21. Effect of -T3X and -T8X Tempers on Tensile Properties of MMC 2124 Al/SiC (B_4C) Extrusions.

Fracture toughness testing was performed in the L-T orientation for the two 2124 MMC extrusions. The compact-tension (CT) specimens were sized to B = 0.30 in. and W = 1.90 in. dimensions. K_Q toughness and yield strength findings are summarized in Table 5. Results for the SiC extrusions are comparable to K_Q values reported in previous development studies. Relatively low toughness values were observed in the B_4C extrusion, despite the attainment of acceptable tensile ductilities. Metallographic sections indicate that an extensive interface region is present in some areas of the extruded bar. Information obtained on the reinforcement type and distribution from the alloy microstructures may provide an understanding of the differences in mechanical property behavior.

3.6 Evaluation of Large Scale PM Billets

A lot of approximately 410 lb. of gas atomized powder was initially produced at Alcoa to satisfy the Task 1 requirements for the PM 2XXX Al alloy. Although melt chemistries were adjusted prior to the atomization run in order to meet target requirements, low solute levels were observed in the final powder samples. Preliminary chemical analyses results for samples taken from the alloy powder lot, designated S. No. 514686 are shown in Table 6.

The low Cu content, and subsequent imbalance of Cu/Mg solute ratio, were a matter of concern with respect to excess S phase formation. A 10 lb. sample of Alcoa atomized powder was packaged and shipped to NASA-LaRC to support laboratory scale evaluations. Laboratory processing trials addressed primarily the issues of alloy chemistry, vacuum hot pressing temperature, and sheet rolling temperature. Metallographic examination of loose powder and consolidated samples at both Lockheed and NASA-LaRC revealed the additional presence of foreign particle inclusions. Due to the improper Cu and Zr alloy chemistries, and contaminants present in the alloy powder, it was decided that the original powder lot (S. No. 514686) was inappropriate for further investigation.

Material	F_{ty}	Specimen Number	Orientation	K_Q (ksi-sq. rt. in.)
2124 Al/SiC	73.0	KSC - 1	L - T	17.4
	73.0	KSC - 2	L - T	15.7
	70.8	KSC - 3	T - L	14.3
	70.8	KSC - 4	T - L	(1)
2124 Al/B_4C	71.6	KBC - 1	L - T	8.9
	71.6	KBC - 2	L - T	11.3
	70.1	KBC - 3	T - L	(1)
	70.1	KBC - 4	T - L	7.2
	69.8	KBC - 5	L - T	9.7
	68.3	KBC - 6	L - T	(1)

NOTE: (1) Failed During Pre-Cracking

Table 5. Preliminary Compact Tension Fracture Properties for MMC 2124 Al/SiC (B_4C) Extrusions, -T8X Temper (350°F/24 hr.).

	Cu	Mg	Mn	Zr	Si	Fe
Target	3.70	1.95	0.20	0.70	-------	-------
Actual	3.38	1.97	0.21	0.35	0.040	0.020

Table 6. Chemical Analyses of 2124 Al Alloy Powder Lot (S. No. 514686).

Technical discussions were initiated between Alcoa and NASA to outline a recovery plan for fabrication and evaluation of 2124 PM alloy products. Program options included the substitution of an available lower strength powder lot, or the atomization of an additional powder lot satisfying the original target compositions.

Two additional powder atomization trials were conducted by Alcoa in an attempt to furnish materials suitable for PM consolidation. A compensation in master alloy content was employed for the two powder runs in order to maintain proper target alloy compositions. High superheat temperatures were also used in an effort to maximize the amount of retained Zr alloying element. Preliminary chemical analyses conducted on samples taken from each powder lot are shown in Table 7.

The primary solute contents for both atomization lots exhibit close agreement with target goals. Since the Cu/Mg solute ratios are nearly stoichiometric, the formation of S phase precipitation predominates in the two alloy compositions. The high Zr levels are instrumental in maintaining an unrecrystallized microstructure in the sheet and plate rolled products. Samples of each powder lot were packaged and shipped to NASA-LaRC to expedite additional laboratory studies. Results from this study demonstrated that high strength, high toughness sheet can be fabricated from the Alcoa powder lots (10). The powder lots were mixed and blended by Alcoa for use in fabrication of the required PM consolidated products. The blended powder from the two atomization runs was denoted as S.No. 514714/5B. Consolidated PM billets were fabricated by Alcoa, and billet slabs were subsequently extruded or forged prior to final product fabrication. Extrusion (modified "T" shape), plate (15 in. X 24 in. X 30 in.), and sheet (0.07 in. X 48 in. X 80 in.) were produced using the appropriate processing parameters for each product form. The -T8X heat treatment was used based on the results from the previous study iteration. A schematic description of the fabrication procedures from the cold compaction to final heat treatment steps is given in Figure 22.

S. No. 514714							
	Cu	Mg	Mn	Zr	Si	Fe	Cu/Mg
Target	3.75	1.85	0.20	0.70	----	----	----
Actual	3.70	1.66	0.23	0.90	0.070	0.030	2.23
S. No. 514715							
	Cu	Mg	Mn	Zr	Si	Fe	Cu/Mg
Target	3.75	1.85	0.20	0.70	----	----	----
Actual	3.94	1.73	0.27	0.90	0.060	0.030	2.28

Table 7. Chemical Analyses of New 2124 Al Alloy Powder Lots (S. No. 514714 and 514715).

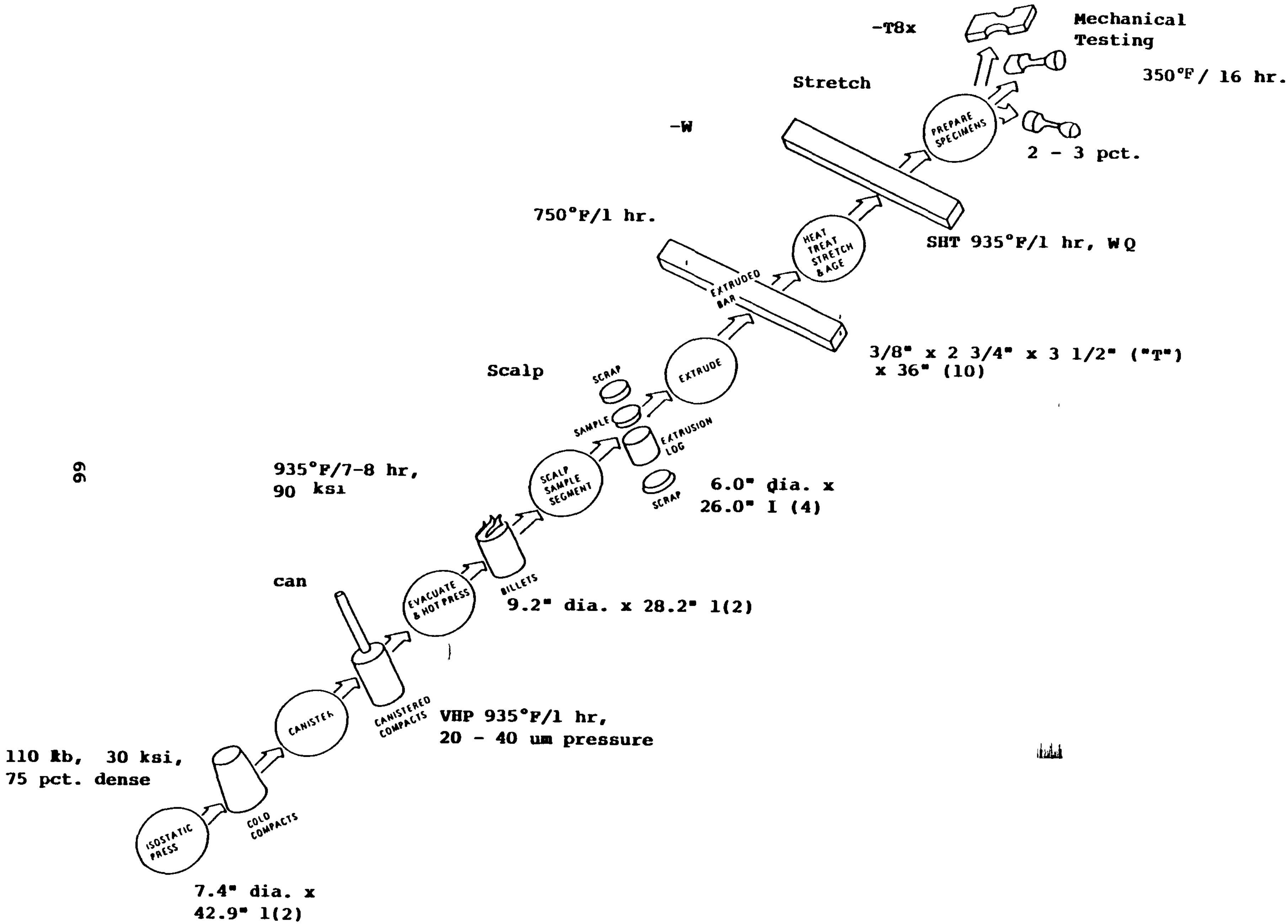


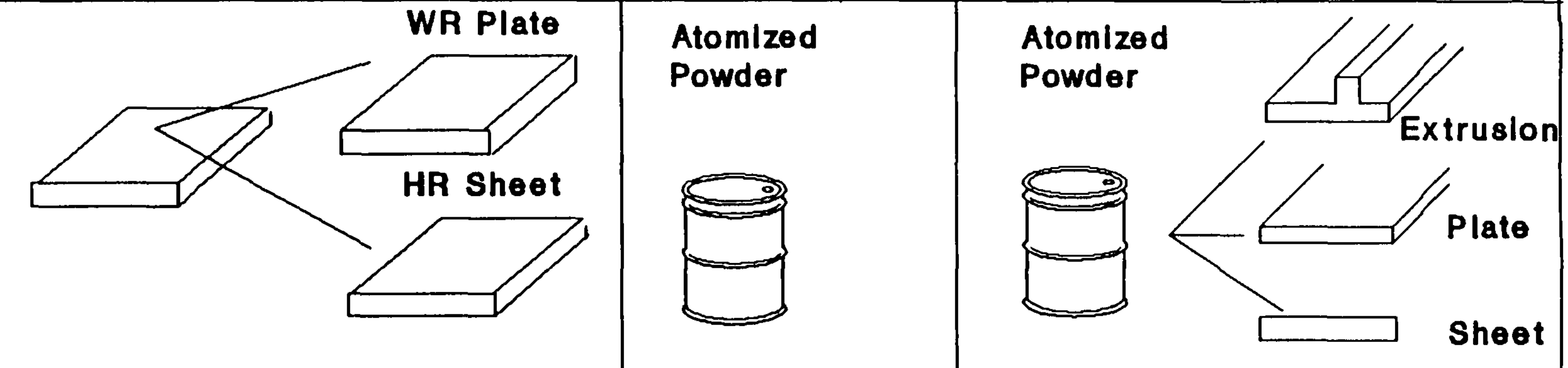
Figure 22. Schematic Diagram of Processing Sequence for PM 2124 Al Alloy Products.

Processing details are similar to previous investigations on PM 2124 Al alloys, and are described in several referenced reports. The PM 2124 Al products evaluated in this portion of the program are shown in Figure 23. Products, billet sizes, and processing difficulties are noted in the figure to indicate program continuity. Laboratory scale billets of 110 lb. were used in the initial studies, with subsequent scale-up to large PM billets of approximately 400 lb.

An initial assessment of the tension strength properties was obtained for the candidate -T8X (350^{o}F/16 hr.) heat treatment temper, identified as near optimum for meeting target goals for PM 2124 Al alloys. A comparison of billet scale-up results for the three product forms of extrusion, sheet, and plate are shown in Figures 24-26 for the new powder atomized materials (S. No. 514714/5B). Both L and LT orientations were evaluated to provide an estimate of the relative anisotropy as a function of PM product form. The lack of aging response from the naturally to artificially aged tempers signifies a major deficiency in all three billet scale-up products. Laboratory scale studies at Lockheed were performed to identify the concerns associated with the weak precipitation hardening response and subsequently low tensile strength properties.

Microstructural examinations indicated that both flat rolled and extruded products were free from inclusions and contaminants observed in previous material lots. The low tensile strength properties appear to be attributable to improper solution heat treatment and cold work content prior to isothermal aging. Further machining and testing of coupon specimens were suspended subject to a resolution of the difficulties associated with heat treatment development. Technical discussions are underway with Alcoa to expedite the re-heat treatment of the PM 2124 Al alloy products to the required -T3X temper. The entire lot of PM 2124 Al alloy products was inventoried at Lockheed and shipped to NASA.

Laboratory Scale Billets		Scale Up Billets	



S. No.	514163	514686	514714/5B
Billet Size (lb.)	110	410	450
Processing Difficulties	Excellent Property Behavior	Improper Cu and Zr Alloy Chemistries, Powder Contamination	Improper Solution Heat Treatment

Figure 23. Billet Processing Scale of PM 2124 Al Products Evaluated in Recent Development Studies.

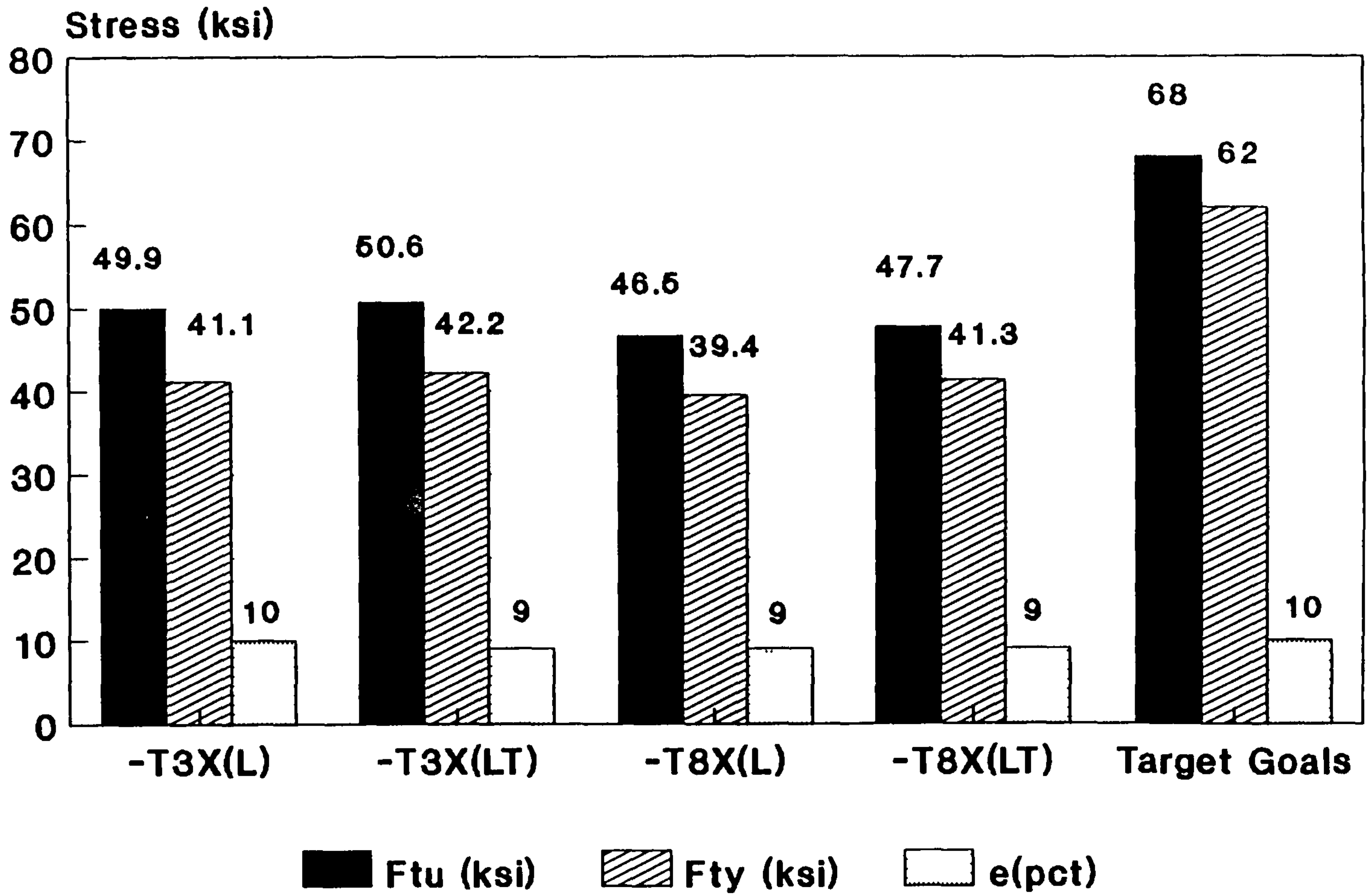


Figure 24. Tensile Properties of PM 2124-Zr Modified "T" Extrusions (S. No. 514714/5B).

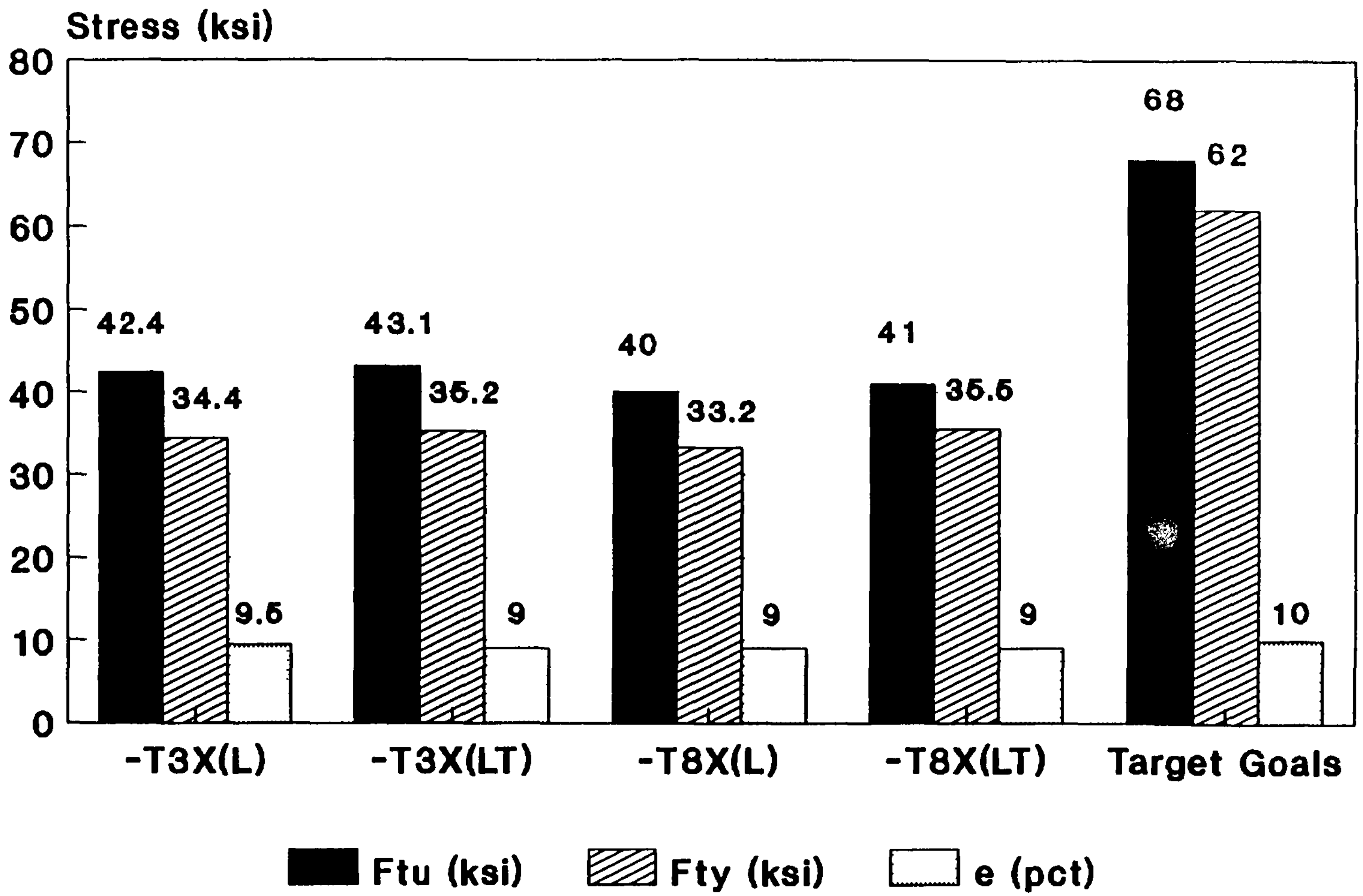


Figure 25. Tensile Properties of PM 2124-Zr Modified Sheet (S. No. 514714/5B).

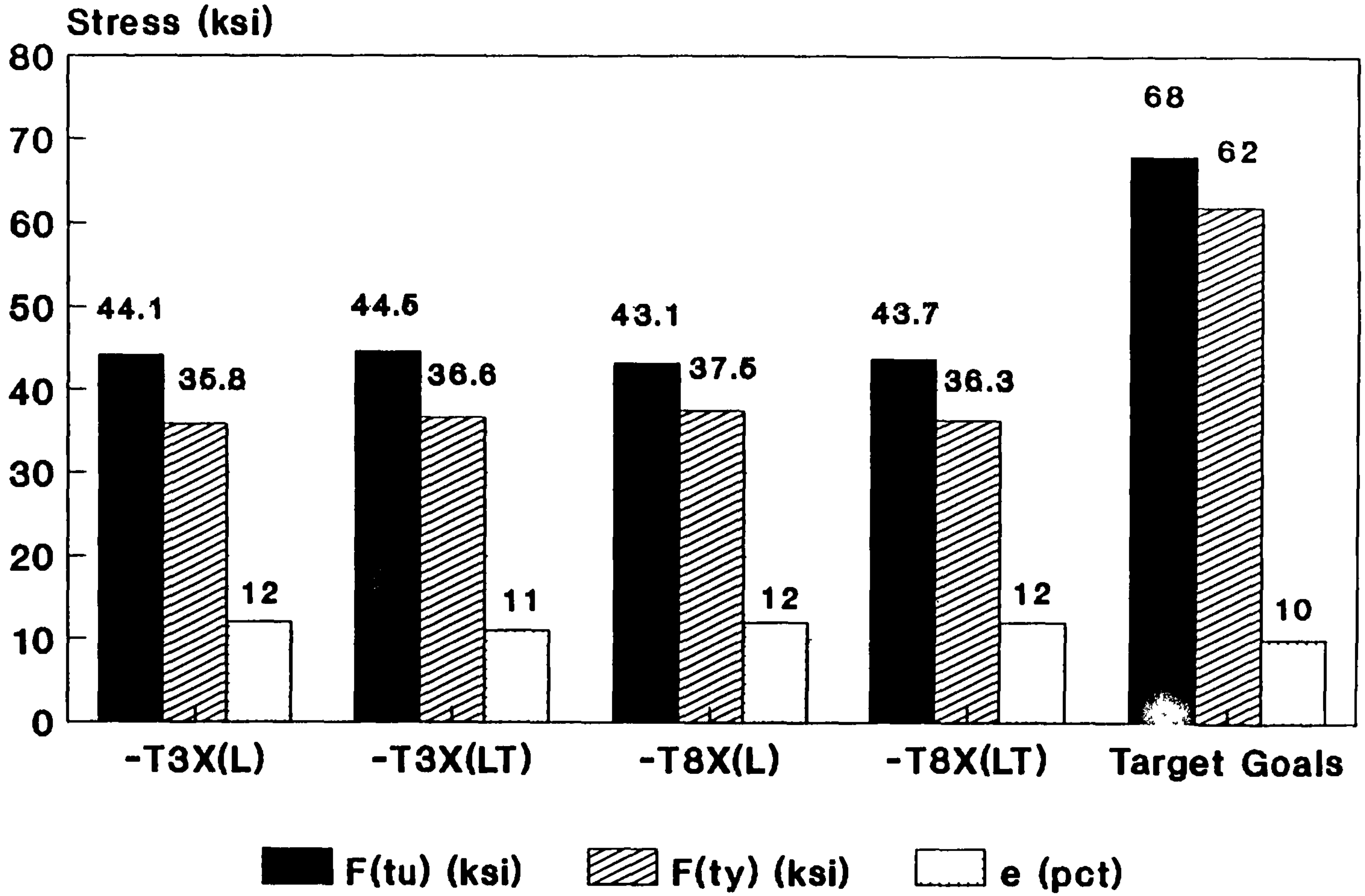


Figure 26. Tensile Properties of PM 2124-Zr Modified Plate (S. No. 514714/5B).

4.0 CONCLUSIONS

All of the PM 2XXX Al alloy plate and sheet studies under this contract have led to the following conclusions:

1. Plate and sheet can be produced with outstanding strength and fracture toughness improvements over IM Al alloys.

2. These alloys show a significant advantage in yield strength properties compared to equivalent IM Al alloys in thin plate and sheet gauges.

3. These materials are unusually more resistant to recrystallization processes (or concomitantly, a greater insensitivity to variations in processing history) than IM Al alloys due to the present of both Al_3Zr and oxide phases.

4. Although recrystallization does occur in thinner gages of the sheet, aging treatments are effective in providing attractive mechanical property behavior.

5. Alloying and processing schedules developed in this program promote unrecrystallized microstructures that are effective in satisfying durability and damage tolerant objectives. An excellent combination of strength, fracture toughness, and fatigue properties can be achieved in sheet and plate products.

6. These products are very sensitive to foreign inclusions which contribute to premature failure and low strength. Proper powder sampling and screening tests are required to ensure the use of high quality constituents.

The SiC and B_4C reinforced 2XXX MMC extrusion studies have led to the following conclusions:

1. Refinements in the composite billet processing led to significant improvements in the solute content of the Al-alloy matrix .

2. Extruded SiC reinforced composites based on 2124 standard and 2124-Zr modified Al alloy compositions exhibited improvements in tensile strength of 25% and in elastic modulus of 45% compared with conventional Al alloys. Tensile properties of these Al/SiC composite materials were shown to exceed the mechanical property goals.

3. Substantial improvements in strain-to-failure were observed for both Al/SiC composite systems, and those were generally attributed to homogenization of solidification defects by using modified SHT schedules. Artificially aged -T6X and -T7X tempers displayed 2 to 3% values of ϵ_f which represents an improvement of nearly 250% compared to previous studies. Tensile elongations or total strain to fracture values remain below the 5 percent goal.

4. An artificially aged heat treatment temper (obtained by 375°F aging) exhibited an optimum combination of tensile strength, elastic modulus, and ductility properties with respect to program objectives.

5. The homogenization of the 2124 Al/SiC_w composites using high temperature soaking treatments was primarily responsible for the overall improvement in property behavior.

6. Extruded products consisting of B_4C_p reinforcements exhibited more isotropic properties compared to SiC_w materials.

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13 ABSTRACT (Maximum 200 words)

This report describes the development and evaluation work completed by Lockheed Aeronautical Systems Company during the period of time from 1980 - 1991 on advanced Al alloy materials in support of the NASA supersonic cruise research project. The technical objective of the materials development was to identify and characterize advanced Al alloys with temperature capabilities extending to 350°F. This report is divided into two sections. The executive summary covers the 1980-1985 timeframe, and provides an overview of the first five alloy development efforts supported under the contract. A number of alloys and fabrication routes were explored with respect to satisfying target goals doe hifh apwws aircraft applications. The second section of the report documents recent developments based on the use of high Zr levels in an optimum Al-Cu-Mg alloy composition. Both unreinforced, an SiC and B_4C reinforced materials were evaluated and compared with conventional Al alloy products. Significant benefits were demonstrated through the use of powder metallurgy processing in terms of durability and damage tolerant properties.

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