ADVANCED POWDER METALLURGY ALUMINUM ALLOYS AND COMPOSITES

W. B. Lisagor and B. A. Stein
NASA Langley Research Center
Hampton, Virginia

INTRODUCTION

Improvements in design properties of structural aluminum alloys over the past three decades had become a slow, evolutionary process as alloy chemistries were developed and refined. By about 1970, the limited equilibrium solubility of alloying additions to 7000- and 2000-series aluminum alloys synthesized by conventional ingot metallurgy (IM) processing portended increasing difficulty in achieving higher levels of balanced properties. However, the emerging technology of rapidly solidified or mechanically alloyed powder metallurgy (PM) aluminum alloys promises to change that situation dramatically.

By employing cooling rates of 10^2 to 10^6°C per second in the production of particulate powders or flakes, alloying element concentrations can be substantially increased through supersaturated solid solutions and grain sizes in consolidated product forms reduced by an order of magnitude from those in conventional ingot metallurgy products. Another method used to achieve small grain size and controlled dispersoid amount and distribution is the mechanical alloying process. Via both processes, the resulting uniform distribution of alloying elements and dispersoids has provided (in laboratory to pilot plant quantity materials) superior property combinations of tensile and creep strength, ductility, fracture toughness, fatigue strength, and corrosion resistance compared to commercial ingot alloys.

The conclusions of a National Materials Advisory Board (NMAB) Survey (reference 1) of advanced powder metallurgy aluminum research were as follows:

- o Rapidly solidified PM alloys offer high potential of superior properties compared to ingot metallurgy alloys.
- o Broad usage of rapidly solidified PM alloys is foreseen for aerospace applications.
- o Current knowledge of phase relationships, microstructure, and structure/property interaction is inadequate.

That survey recommended vigorous support of rapidly solidified PM aluminum at all levels of research, development, testing, and manufacturing, with special emphasis on continuing long-range basic research and development programs.

This paper outlines the differences between powder and ingot metallurgy processing of aluminum alloys, indicates the potential payoff in the use of advanced PM aluminum alloys in future transport aircraft, and reviews briefly the national program (in response to the NMAB challenge) to bring this technology to commercial fruition and the NASA Langley Research Center role in this program. We also present some initial results of research in 2000-series PM alloys and composites to highlight the property improvements possible.

CONVENTIONAL INGOT METALLURGY

The mature technology in structural aluminum alloys for aerospace, ground, and water transportation and for a wide range of consumer products is a result of two generations of developments and refinements of ingot metallurgy (IM) processes. The aluminum metal is recovered from its ore, usually bauxite, by an electrolytic process. As figure 1 shows, the alloy constituents are melted and a direct casting process using water-cooled molds produces ingots of various sizes. Cooling rates as high as 10°C per second may be achieved by this method but IM cooling rates for aluminum alloys are generally lower and can be as low as 10^{-2}°C per second for large ingots. Thus, equilibrium restrictions of solid solubility limit ingot chemistries, and grain sizes in ingots are relatively coarse. The cast ingot is warm- and/or cold-worked by forging, extrusion, or rolling to produce the mill product form. The latter is heat treated (or thermomechanically processed), which consists of solution treatment plus precipitation hardening (plus cold work) for structural alloys, then formed or machined to final product dimensions.

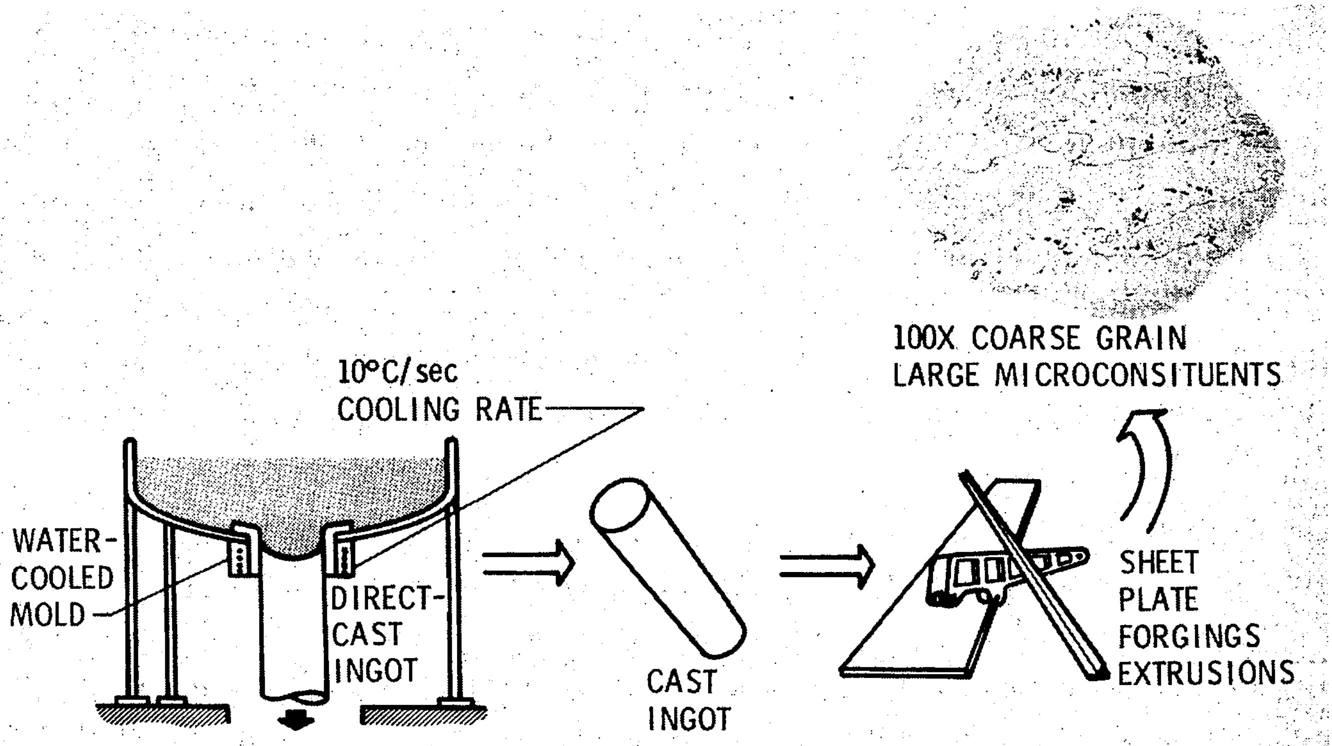


Figure 1

RAPIDLY SOLIDIFIED OR MECHANICALLY ATTRITED POWDER METALLURGY

Two generic processes are currently being commercialized to produce aluminum alloy powders for subsequent consolidation into billets which are then converted into product forms and structural components using conventional aluminum processing and fabrication technology. The powder process under most extensive study is that of rapid solidification from the melt. As illustrated in figure 2, one process to produce such powders is to impinge a jet of molten alloyed aluminum from a vacuum melting furnace onto a rapidly spinning disk in an inert gas quench chamber; the "atomized powders" which result are roughly spherical and micron-sized. Alternative versions of this process can produce other micromorphologies such as very thin flakes or ribbons. The cooling rates achieved typically range from 10^2 to 10^6°C per second. The powders produced can retain relatively high percentages of alloying elements (miscible in the melt) in metastable, supersaturated solid solutions. Supersaturation opens up a wide range of possibilities for new aluminum alloy chemistries which could not be produced by conventional ingot melting techniques (with their slow cooling rates), because equilibrium solid solubility of many elements in aluminum is at low concentrations.

The other generic powder production process - mechanical alloying - is also illustrated in figure 2. Elemental and/or partially prealloyed powders of the alloy chemistry desired are subjected to high energy mixing processes which result in a powder in which each particle contains all desired alloying constituents in a uniform chemical/dispersoid distribution. Figure 2 shows this result achieved in a high energy ball mill with steel balls driven by a rotating impeller in a water-cooled tank. The steel balls pressure weld the aluminum, iron, and other elemental powders into micron-sized prealloyed powders.

The fine powders resulting from both generic processes should have these desirable qualities: (1) relatively uniform matrix chemistry with controlled levels of alloying elements, (2) fine, uniformly spaced, thermally stable dispersoids (i.e.-oxides and/or intermetallics).

In either case, the powders are classified and packaged, usually in metallic cans, prior to cold compaction. Cold compacts are vacuum degassed followed by hot compaction in a conventional set of dies or by hot isostatic pressing to produce a billet (compacted ingot) of fine grain size compared to a cast ingot.

The subsequent rolling, extrusion, forging, and heat treating/thermomechanical processing procedures for the powder metallurgy billets are similar to those used for the cast ingot products, using equipment currently available in aluminum material producer, aerospace, and consumer product industries. Parameters of the particular cold/hot working or heat treatment process will probably be somewhat different for powder product forms (to achieve optimum balanced properties) than they were for cast ingots of similar chemistry. Considerable research is under way to investigate such parameters. Conventional aluminum alloy component mechanical joining processes (e.g.-riveting, bolting) should be applicable to the advanced PM alloys. Development of welding procedures to retain the desired properties may be very difficult; however, PM alloys will likely be used in applications where welding is not a primary joining method.

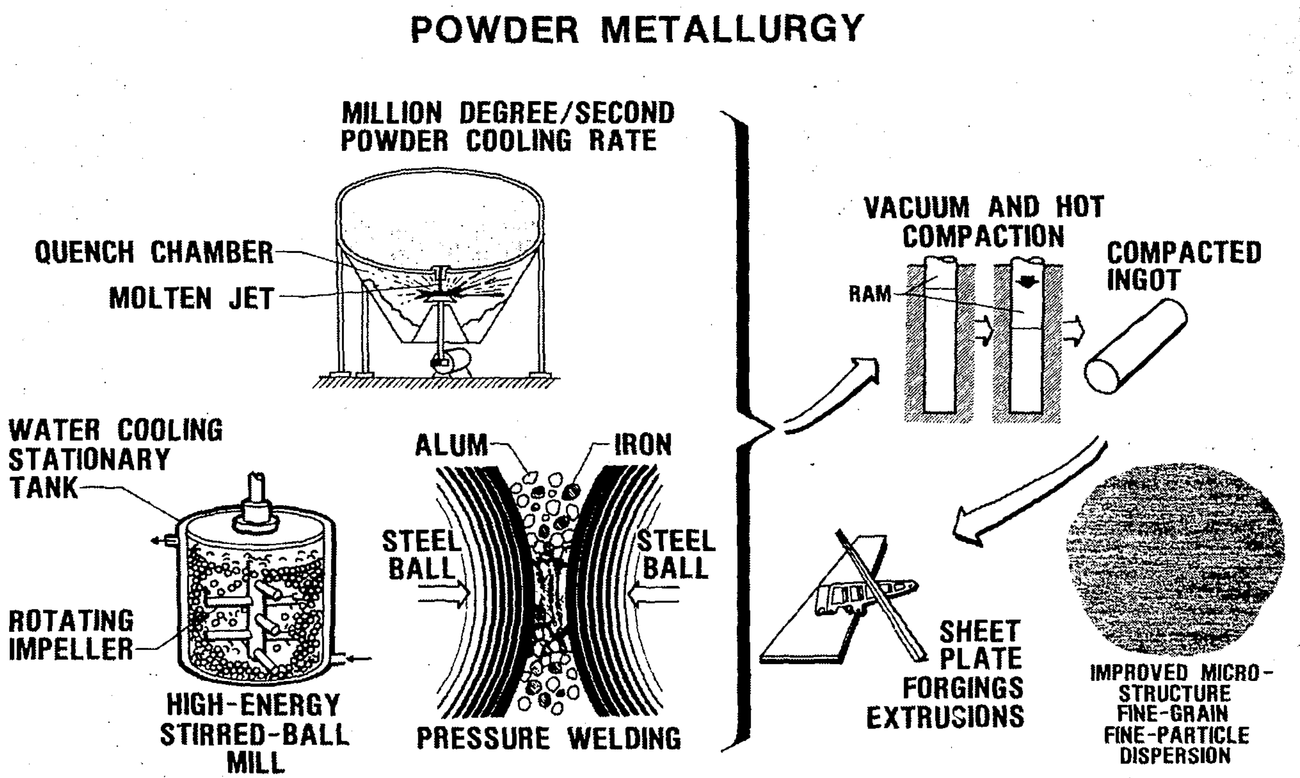

POWDER METALLURGY
MILLION DEGREE/SECOND POWDER COOLING RATE
QUENCH CHAMBER
MOLTEN JET
WATER COOLING STATIONARY TANK
ROTATING IMPELLER
HIGH-ENERGY STIRRED-BALL MILL
ALUM
IRON
STEEL BALL
STEEL BALL
PRESSURE WELDING
VACUUM AND HOT COMPACTION
RAM
COMPACTED INGOT
SHEET PLATE FORGINGS EXTRUSIONS
IMPROVED MICRO-STRUCTURE FINE-GRAIN FINE-PARTICLE DISPERSION

Figure 2

STATUS OF NATIONAL ADVANCED ALUMINUM ALLOY PROGRAM

The national technology development program in advanced aluminum alloys is a more or less coordinated effort of materials producers and aerospace manufacturers, with Federal Government support in most areas. That support is provided mainly by the Department of Defense, with significant contributions from the U.S. Air Force, Army, Navy, and Defense Advanced Research Projects Agency, particularly in the materials development and applications areas. NASA support is generally aimed at the materials research area.

The strong direction to date in materials research (figure 3) has been aimed at minor chemistry and heat treatment modification of the conventional ingot metallurgy 7000-series (Al-Zn-Mg-Cu-X) and 2000-series (Al-Cu-Mg-X-X) alloys to take advantage of the small grain size/uniform dispersoid capabilities of the powder process without making major diversions from known aluminum alloy technology. Only limited alloy formulation of entirely new chemistries in powder metallurgy aluminum alloy has been pursued to date. Most notable of these is the development of Al-Fe-Ce alloys and other chemistries which produce thermally stable dispersoids for applications at temperatures above 400°F. Another research area receiving increased recent emphasis is aluminum-lithium alloys synthesized by both ingot and powder metallurgy techniques. Al-Li-X-X alloys promise important increases in elastic modulus-to-density ratios compared to conventional alloys at moderate temperatures, an important factor in stiffness critical applications.

Materials development has been under way for several years with some government support, but largely financed by the major aluminum suppliers - ALCOA, Kaiser, and Reynolds - for the rapidly solidified powder alloys and by INCO/Novamet for the mechanically alloyed materials. There have been commitments to commercial development with ALCOA rapidly solidified powder alloy X7091 and the INCO IN9021 mechanically alloyed material. Further alloy chemistry/processing development studies are under way at several companies and pilot process scaleup has been initiated.

Applications of advanced aluminum alloys have been studied for several years by major aerospace manufacturers (e.g.-Lockheed, Boeing, McDonnell Douglas, Northrop, General Dynamics/Convair), under both company and government funding. Evaluations to date have covered a broad range of material property tests of laboratory specimens from laboratory or pilot-plant quantities of material. The materials data have been used in preliminary design studies to forecast the most promising applications. Specific aerospace structural applications with high potential payoffs have been identified and the "spinoff" to nonaerospace applications has been addressed. The most promising potential nonaerospace applications for advanced aluminum alloys appears to be in ground transportation.

STATUS OF NATIONAL ADVANCED ALUMINUM ALLOY PROGRAM

- MATERIAL RESEARCH
  - GOVERNMENT/PRODUCER/USER COMBINED R&D EFFORTS
  - FOCUS ON MODIFICATION OF I/M CHEMISTRIES IN 2000- AND 7000-SERIES ALLOYS
  - NEW ALLOY FORMULATIONS FOR HIGH-TEMPERATURE APPLICATIONS
  - Al-Li ALLOYS
- MATERIAL DEVELOPMENT
  - MAJOR MATERIAL SUPPLIERS INVOLVED
  - COMMITTED TO COMMERCIAL DEVELOPMENT
  - PILOT PROCESS SCALEUP INITIATED
- APPLICATIONS
  - BROAD PROPERTY EVALUATION BY MAJOR AEROSPACE MANUFACTURERS AND GOVERNMENT UNDER WAY
  - ALL EVALUATIONS TO DATE BASED ON LABORATORY QUANTITIES
  - POTENTIAL NONAEROSPACE USAGE IN ADVANCED GROUND TRANSPORTATION SYSTEMS

Figure 3

ADVANCED ALUMINUM ALLOY TECHNOLOGY: RESEARCH AND DEVELOPMENT COSTS

The cost of bringing each new advanced aluminum alloy from the initial synthesis through the research and development (R&D) stage to the application stage - is shown in figure 4. It takes about 3 years of materials research with cumulative costs accruing relatively slowly to reach the point where a decision to scale up to product form characterizaton and structural element testing can be made. That stage and the following pre-application stages, design property generation and proof-of-concept testing of complex structures, consume rapidly increasing funding to about the 5th year. When a positive application decision is reached, R&D support is usually required to enhance the material for the specific application and to solve material/processing problems in the early production runs. The total cost of this R&D effort in today's dollars is $6- to $10-million for each alloy brought to full commerical production.

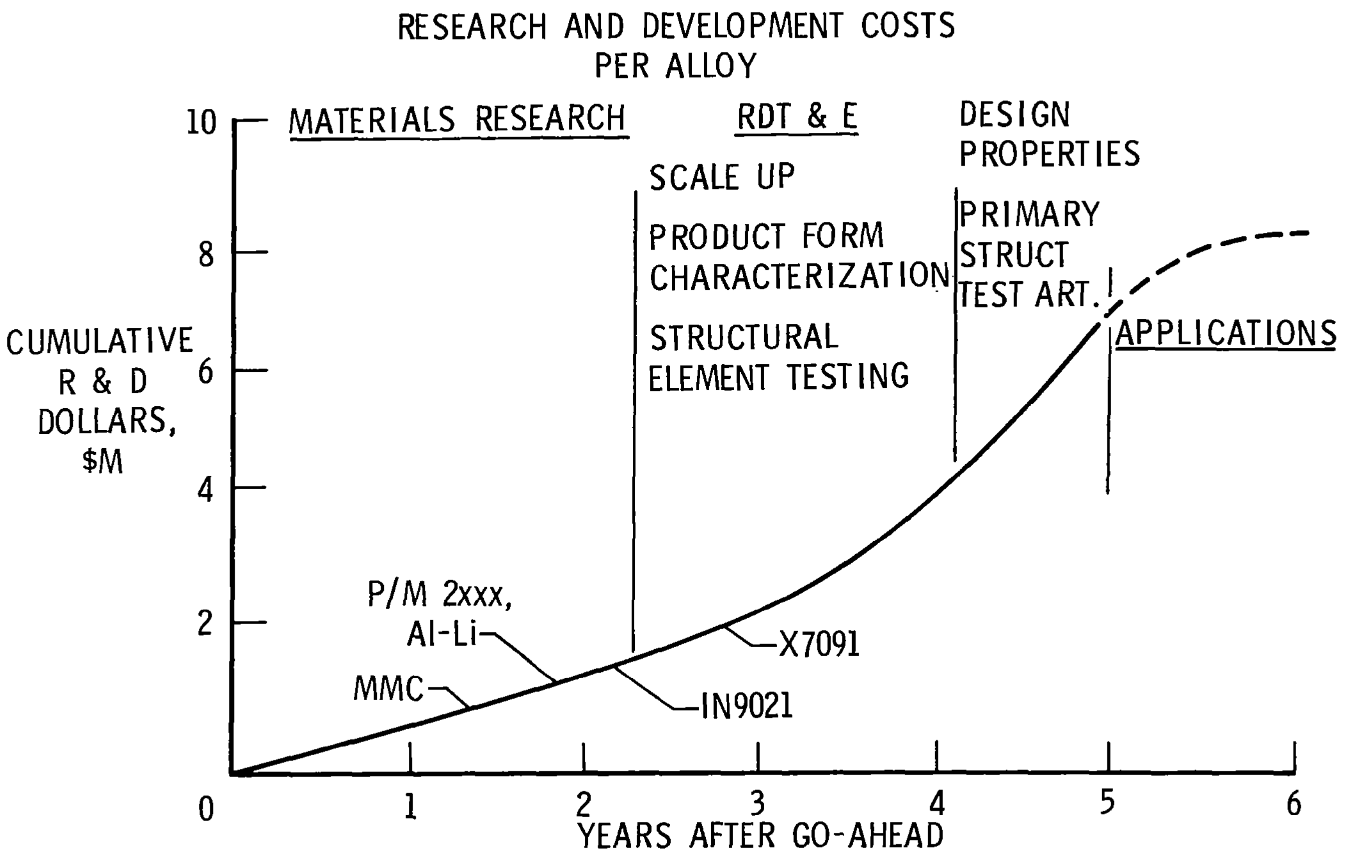


Figure 4

RELATIVE COST DIFFERENTIAL FOR CONVENTIONAL AND ADVANCED ALUMINUM ALLOYS: LONG-HAUL TRANSPORT APPLICATIONS

As in any other application, the aerospace industry must convince itself that increased costs inherent in a new technology will be more than offset by the advantages resulting from that technology, in a specific product or component. This subject was addressed in a NASA supported study for three types of commercial vehicles - a long-range transport aircraft, a short/medium-range transport aircraft, and a short-haul commuter aircraft (reference 2). Examples of the results are shown in figures 5 through 7.

The relative cost differentials between conventional commercial ingot Al alloys and advanced aluminum alloys is shown in figure 5. Cost per pound of material or structure is shown in 3 sets of bars, with the costs plotted on a logarithmic scale. The raw material (in sheet, plate, extrusion or forging product form) costs of conventional alloys ranges from about $2.25 to $4.50 per pound; the advanced alloys are twice to four times as expensive. However, a comparison on that basis only can be highly misleading. The center bars in the figure indicate the actual costs per pound of a structural component produced with conventional alloys ranges from about $92 to $114 per pound; the related components in advanced alloys will cost about 20 percent more. The two bars on the right, which reflect the total aircraft production cost per pound of structural weight, show a further reduction in the cost differential between conventional and advanced aluminum to about 16%. When the weight savings is taken into account, the projected cost per aircraft using advanced aluminum is actually slightly lower than its conventional aluminum counterpart, as indicated in figure 6.

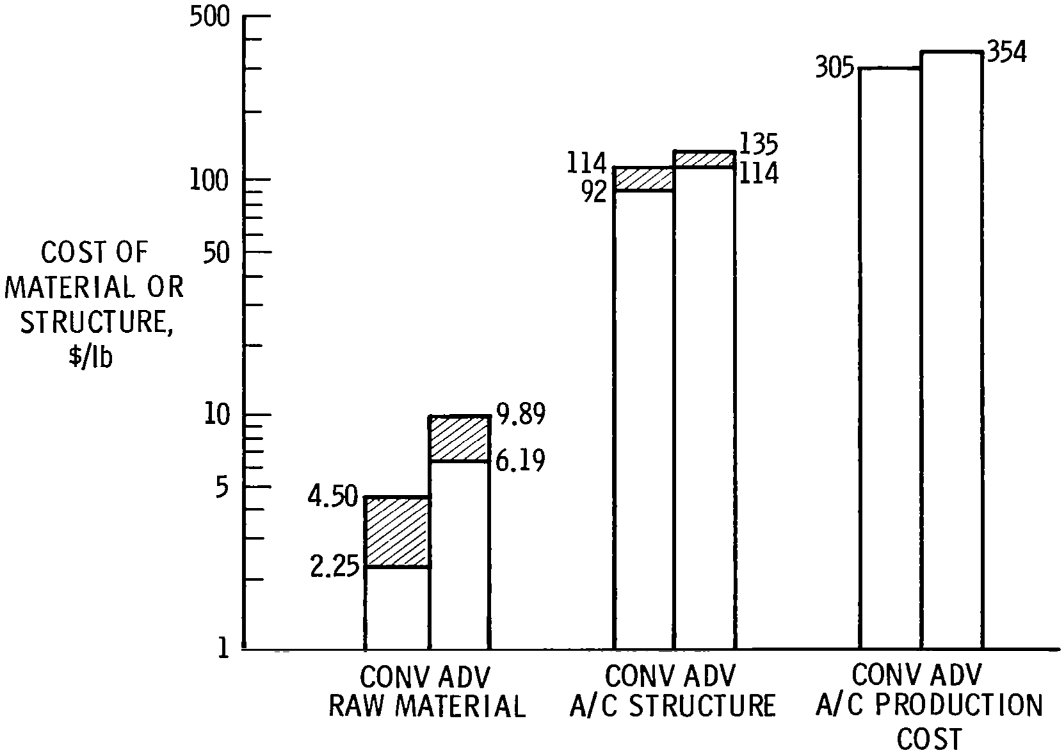
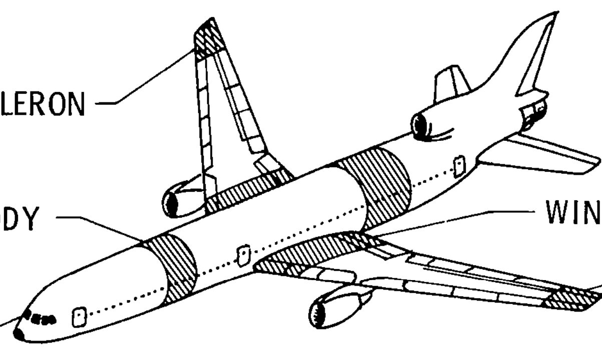


Figure 5

ADVANCED LONG-RANGE TRANSPORT FOR THE 1990s: NET VALUE OF ADVANCED ALUMINUM TECHNOLOGY

The most attractive generic aircraft application of advanced aluminum alloy technology found in the study reported in reference 2 is the long range transport. A sketch of such a vehicle, an extension of Lockheed L-1011 technology, is in figure 6. This concept was analyzed for a primary structure of either conventional aluminum or advanced aluminum alloy. The shaded areas indicate major structural and aerodynamic improvements from the current aircraft. The 1990s aircraft also has composite secondary structure components and improved flight station electronics, controls, etc.

The table in the lower part of figure 6 shows that (in spite of the increased costs per pound of advanced material and structure shown in figure 5), the increased structural efficiency (i.e. - decreased structural weight fraction) of the advanced aluminum aircraft shows a cost benefit in all significant cost factors. Most importantly, the operational cost per year benefit for a fleet of 300 aircraft is highly significant even at fuel costs at $1.00 per gallon and rises sharply as fuel price increases. The specific property improvements required in the advanced Al alloys to achieve these benefits are addressed in the next figure.



ATX-3501 LONG RANGE TRANSPORT AIRCRAFT	TOTAL OPERATIONAL COST* FUEL PRICE, $			FLYAWAY COST, $		RDT&E COST, $
	264/m^3 (1.00/gal)	528/m^3 (2.00/gal)	792/m^3 (3.00/gal)	PER AIRCRAFT	300 AIRCRAFT	300 AIRCRAFT
REFERENCE AIRCRAFT (CONVENTIONAL ALUMINUM)	10585M	12779M	14948M	68.49M	20547M	2823M
ADVANCED ALUMINUM AIRCRAFT	10265M	12275M	14271M	66.79M	20037M	2753M
NET COST BENEFIT	320M	504M	677M	1.70M	510M	70M

*ANNUAL COST FOR 300 AIRCRAFT BASED ON AVERAGE STAGE LENGTH OF 4630km (2500 n. mi.)

Figure 6

PRELIMINARY MATERIAL PROPERTY GOALS

It is important to realize that in any complex structure, materials are utilized in a variety of product forms and specific components put a premium on different properties and combinations of properties. Thus, several different alloys (or the same alloy with different thermomechanical treatment to enhance given properties) are utilized in conventional aluminum alloy aircraft structures. Accordingly, several types of advanced alloys are envisioned for future applications. Increases in a given property, such as strength or stiffness, will usually not be enough to satisfy the goals. A balance of properties is required, with an increase over the current alloy in several parameters and at least comparable values in other properties.

A preliminary set of material property goals to achieve the benefits shown in the the preceding figure is shown in figure 7. The table shows that the aircraft structural applications can be divided into five classifications, from strength to low-density/high-stiffness (left-hand column). The product forms and typical conventional alloys used in current long-range transport structures are indicated in the center columns. One to three product forms are utilized in each classification. The right column shows the target goals as percentage increases in various properties for each classification. An advanced alloy must meet or exceed these targets to provide the required structural benefits. However, substantial exceedence of one property without maintaining the required balance of properties usually will not achieve the desired result.

CLASSIFICATION ALLOY REQUIREMENT	ALLOY CODE	BASELINE ALLOY-PRODUCT FORM				TARGET GOALS PERCENT IMPROVEMENT
		SHEET	PLATE	EXTRUSION	FORGING	
STRENGTH	A	7075-T6 clad	–	7075-T6	–	20-25% STRENGTH 20% FATIGUE COMPARABLE TOUGHNESS
STRENGTH AND CORROSION RESISTANCE	B	–	7075-T76	7075-T76	7075-T73	20-30% STRENGTH 20% FATIGUE COMPARABLE TOUGHNESS & CORROSION RESISTANCE
STRENGTH, STIFFNESS AND CORROSION RESISTANCE	C	–	7075-T76	7075-T76	–	10-20% STRENGTH 10% FATIGUE 8% STIFFNESS COMPARABLE TOUGHNESS & CORROSION RESISTANCE
DURABILITY AND DAMAGE TOLERANCE	D	2024-T3 clad	2024-T3	–	–	20% FATIGUE 25% TOUGHNESS CORROSION RESISTANCE COMPARABLE TO 7075-T76
LOW DENSITY/ HIGH STIFFNESS	E	2024-T3 clad	–	–	–	10% FATIGUE 10% DENSITY COMPARABLE STRENGTH

Figure 7

LaRC ADVANCED ALUMINUM ALLOY PROGRAM PHILOSOPHY

Considering the national Advanced Al Alloy Program (figure 3) and the conclusions and recommendations of the NMAB Study (see Introduction), the decision was made to focus the LaRC program on research aimed at a quantitative understanding of structure property relationships in advanced aluminum alloys. The elements of this program philosophy are shown in figure 8. The five elements at the left (composition.....thermomechanical processing....product form processing) are all factors which will affect the microstructural qualities listed in the center (grain and subgrain structure...microconstituent particles) and, in turn, must be adjusted to achieve desired microstructures or microstructural distributions. The latter are directly related to the three elements listed at the right, the physical and mechanical properties (including those which are time dependent). Learning and quantifying these structure-property relationships will enable prediction of new chemistry/processing directions for further PM aluminum improvements, understanding of difficulties encountered in the application of these advanced alloys, and thus (as the information is digested in the materials and fabrication communities) the tailoring of aluminum properties for aerospace structures.

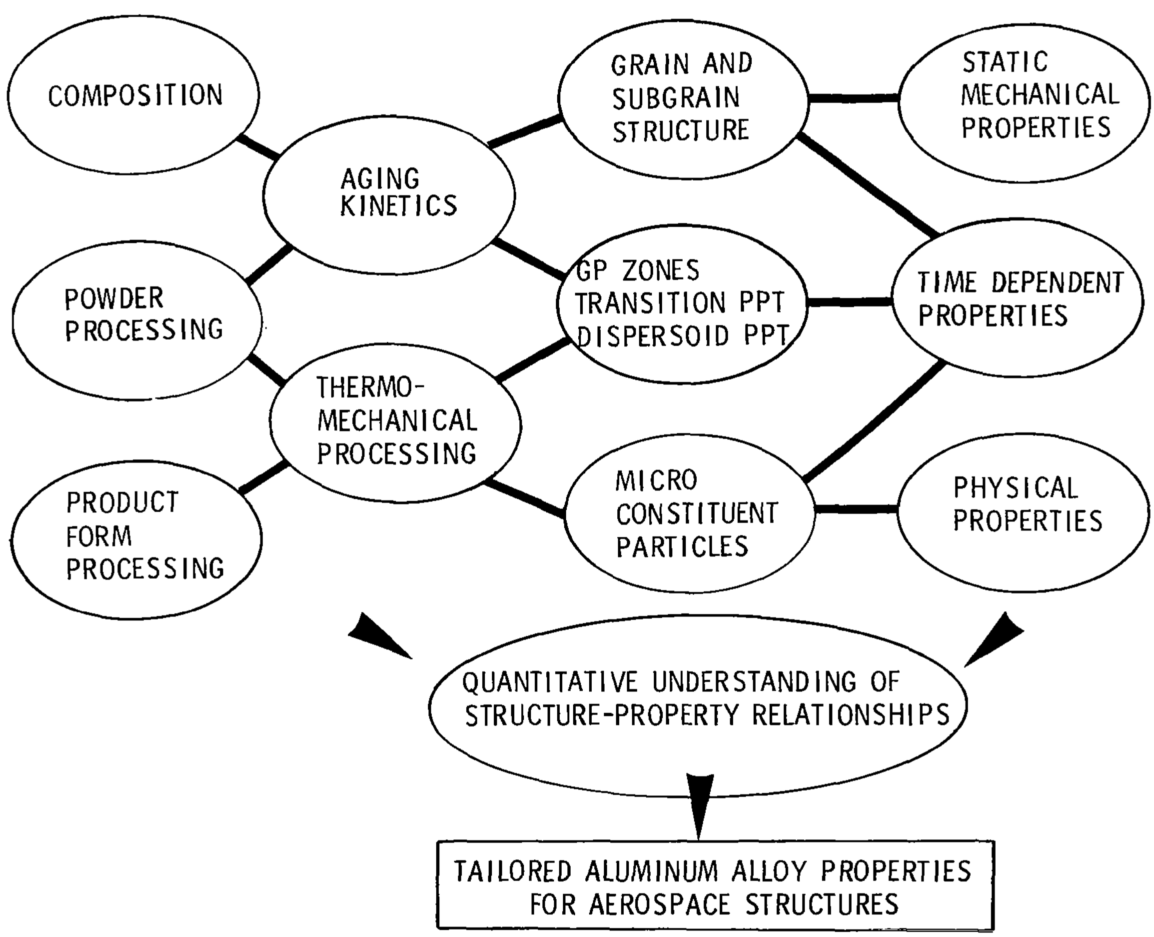


Figure 8

LaRC ADVANCED ALUMINUM ALLOY PROGRAM APPROACH

Implementing the philosophy shown in figure 8, and narrowing the range of possible aluminum alloy types to be studied, LaRC decided to concentrate on the alloy chemistry developed for high-toughness, intermediate-temperature (to about 350°F in long cumulative service) applications. That family is the 2000-series alloys, the Al-Cu-Mg-X-X chemistries. As indicated in Figure 9, the focus will be on understanding of: (1) the possibilities in powder chemistry/processing optimization, (2) the structure-property relationships, (3) aging kinetics and thermomechanical processing variables; and (4) component processing methodology opportunities. The program will be a combined effort of in-house, contract, and university grant activity. Selected results of initial powder metallurgy alloy studies are shown on the following figures.

- CONCENTRATE ON Al-Cu-Mg-X-X CHEMISTRY
- FOCUS ON UNDERSTANDING
    - POWDER CHEMISTRY/PROCESSING OPTIMIZATION
    - STRUCTURE-PROPERTY RELATIONSHIPS
    - AGING KINETICS AND THERMOMECHANICAL PROCESSING
    - COMPONENT PROCESSING METHODOLOGY
- COMBINED IN-HOUSE, GRANT, AND CONTRACT ACTIVITY

Figure 9

COMPARISON OF NOTCHED TENSILE STRENGTH/YIELD STRENGTH RATIOS

Implementation of the LaRC advanced aluminum alloy research program has concentrated to date on the systems study of transport aircraft (results of which are described previously herein) and on studies to evaluate the potential of 2000 series PM aluminum alloys with chemistry modifications from the corresponding IM alloys (ref. 3). Laboratory quantities of several 2000-series powder alloys have been evaluated, including 2124, 2219, and the 2124 alloy with silicon carbide whisker reinforcement.

The objective of this part of the LaRC effort is to determine powder metallurgy chemistries/heat treatments on 2000-series alloys which can meet the target material property goals for advanced transport aircraft shown in figure 7. The chemistry modifications have been limited initially to adjustments in the amount of dispersoid forming elements present in the PM product. The purpose of these adjustments was to promote formation of more thermally stable dispersoids and to take advantage of the naturally occurring oxide dispersoids present in the P/M product. The desired result is an increase in yield strength at ambient and elevated temperatures while maintaining high toughness.

Figure 10 shows recent results indicating that combined goals of tensile yield-strength and toughness (as measured by notched tensile strength) can be met with extrusions of powder metallurgy aluminum alloys. The dashed line for the ingot metallurgy 2124-T8510 alloys shows that data for specimens of this material do not meet the goal, falling below or to the left of the target goal outlines. The powder metallurgy, modified chemistry form of the 2124 alloy with the similar heat treatment can reach the notch strength ratio target goal at a yield strength of about 62 ksi. Similarly, certain PM chemistry modfications of the 2618 alloy can meet the goals at yield strengths from about 62 to 65 ksi, whereas the 2618 PM alloy with the identical chemistry of the IM alloy does not meet the goals. The P/M HID 543 alloy can also meet the goals at yield strengths of about 63 ksi.

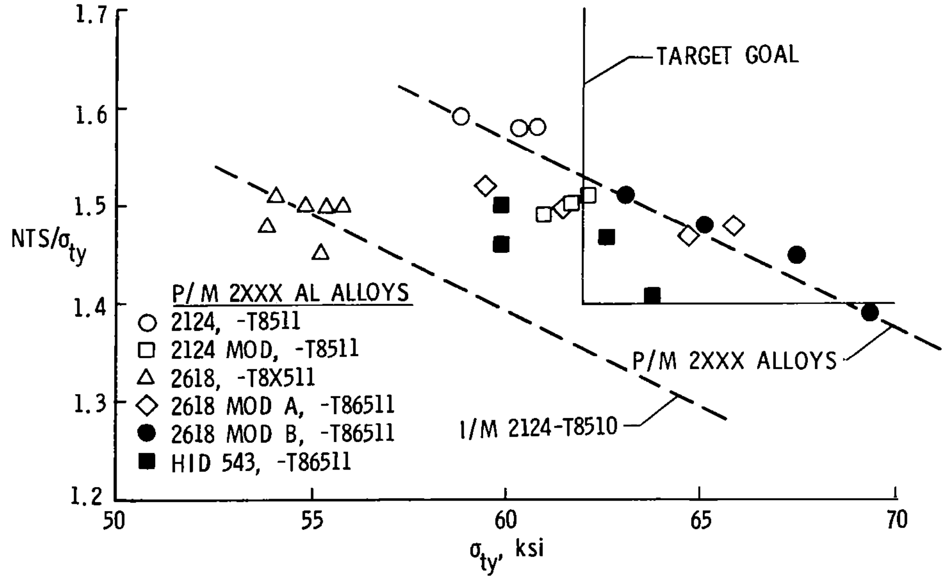


Figure 10

COMPARISON OF TENSILE PROPERTIES FOR PM 2219 Al

Improving the properties of an aluminum alloy via powder metallurgy is achieved through a combination of parameters. Minor chemistry modifications are made in the alloy to take advantage of the inherent capability of the powder process to retain higher percentages of strengthening elements in solid solution and to distribute dispersoids more finely and uniformly than is possible with ingot alloys. Solution treatment and aging or thermomechanical treatment conditions usually require modifications for the powder metallurgy alloy to achieve the best balance of properties in the advanced material.

A case in point is shown in figure 11. The ultimate tensile strength (σ_{tu}), tensile yield strength (σ_{ty}), elongation (e), and reduction in area (RA) are shown for extruded bars of conventional 2219 alloy (Al-6.3 Cu-0.3 Mn-0.2 Zr) ingot material and for the PM alloy modification of it (Al-5.5 Cu-.35 Mg-.3 Mn) after several temperature/time conditions of solution treatment (ST) and aging. It is generally desirable to process P/M alloy product at the lowest temperatures practicable in order to retain the uniformity of chemistry and dispersoids inherent in the powders. Attempts to solution treat at temperatures below that of conventional processing were made to limit tendency for recrystallization and grain growth. Figure 11 shows that P/M alloy properties can be altered significantly by solution treat temperature, but that highest strengths were attained at a solution treat temperature near that of the conventional I/M alloy. However, strength improvements were obtained for all P/M conditions.

TENSILE PROPERTIES FOR P/M 2219 Al MOD - T8511 TEMPER

MODIFIED SOLUTION TREATMENT SCHEDULE

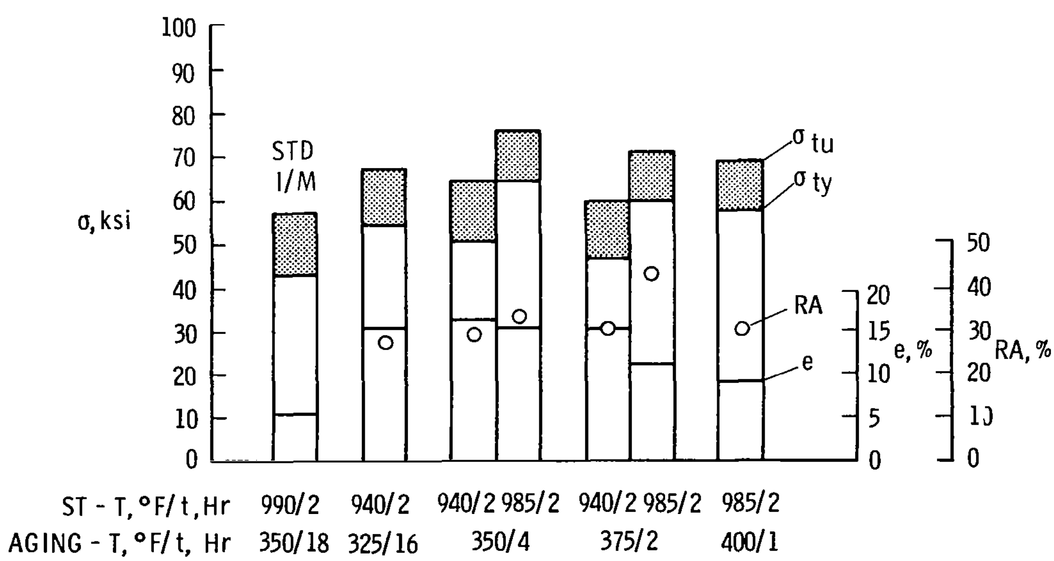


Figure 11

SPECIFIC ELASTIC MODULUS OF 2124 AND 2219 Al MMC/SiC EXTRUSIONS

Another advantage of the powder metallurgy process is its capability to consolidate alloys with uniform dispersions of high-strength, high-stiffness microconstituents which can further enhance important design properties of advanced aluminum alloys.

Two 2000-series alloys were fabricated with different amounts of silicon carbide whiskers (nominal 0.5 μm diameter with typical length/diameter ratio of 60) to produce whisker-reinforced metal matrix composites, and heat treated to the T4 condition. As shown in figure 12, small extrusions exhibit very attractive specific elastic moduli compared to the conventional 2000-series ingot metallurgy alloy, IM 2024-T4 (dashed curve). The four solid curves show that the specific elastic modulus for two powder aluminum alloys, 2124-T4 and 2219-T4, each reinforced with 15 and 25 percent silicon carbide whiskers (SiC_W) is 30 to 75% higher than the IM 2024 over a temperature range from 75 to 350°F. Many aerospace structural components are stiffness limited. Such improvements in specific stiffness can be highly significant, if other properties can be maintained at adequate levels for each specific design.

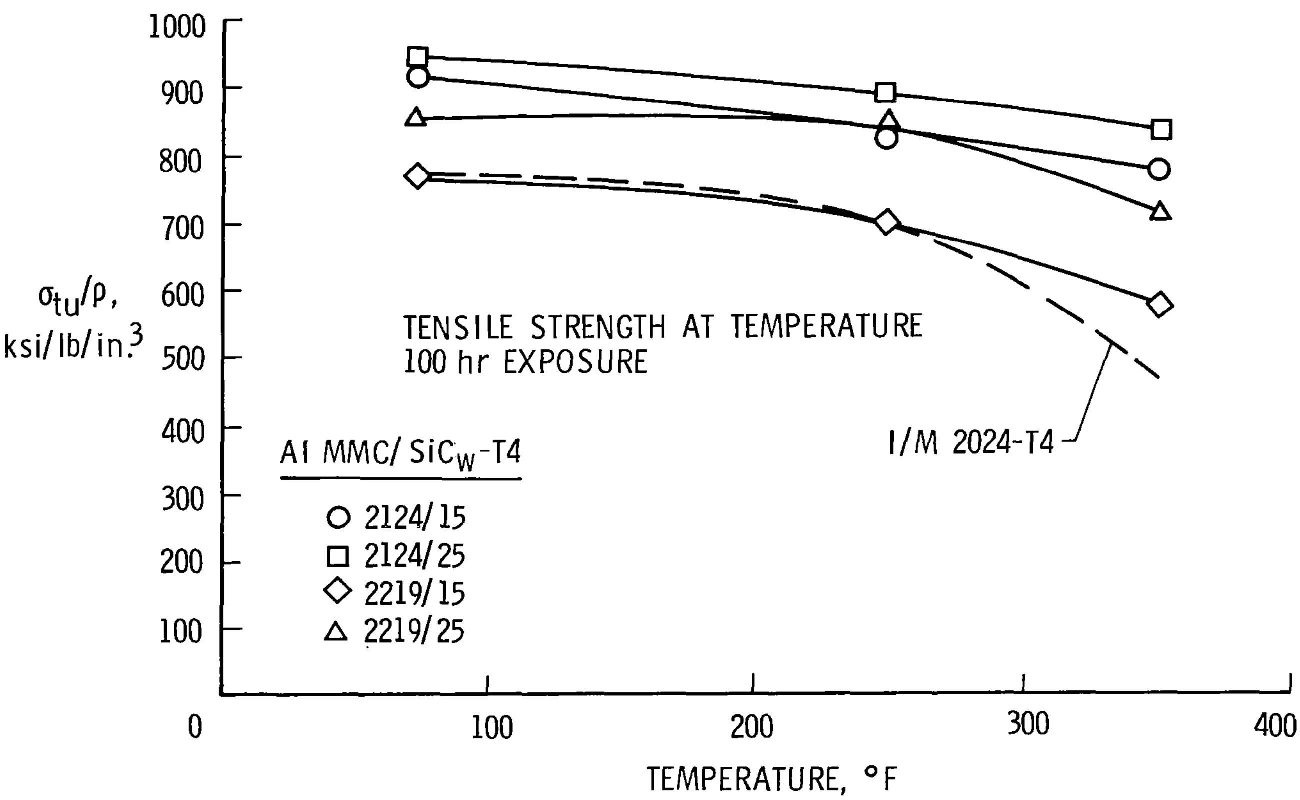


Figure 12

SPECIFIC TENSILE STRENGTH OF 2124 and 2219 Al MMC/SiC EXTRUSIONS

Figure 13 shows the specific tensile strength data which corresponds to the specific elastic modulus data shown for the SiC whisker reinforced aluminum alloys in figure 12. Specific strengths ranged from equivalent to unreinforced IM 2024-T4 for the 2219-T4 with 15 percent whiskers to a 21 percent increase over I/M 2024-T4 for PM 2124-T4 with 25% SiC_w at room temperature. At 350°F (after 100 hrs exposure at 350°F) specific strength increases over IM 2024-T4 ranged from 25% for PM 2219-T4 with 15%SiC_w to 73 percent for PM 2124-T4 with 25% SiC_w in the laboratory extruded bar specimens. However, current materials have typical elongations to failure of less than 3%, a property which must be improved if conventional philosophy is to be utilized in designing with these metal matrix composites. Further research is needed to enhance ductility in these materials, to develop these properties in other product forms such as sheet and plate, and to scale up to large billets, but the promise of these powder metallurgy aluminum matrix composites, especially for elevated temperature aerospace structural applications, appears bright.

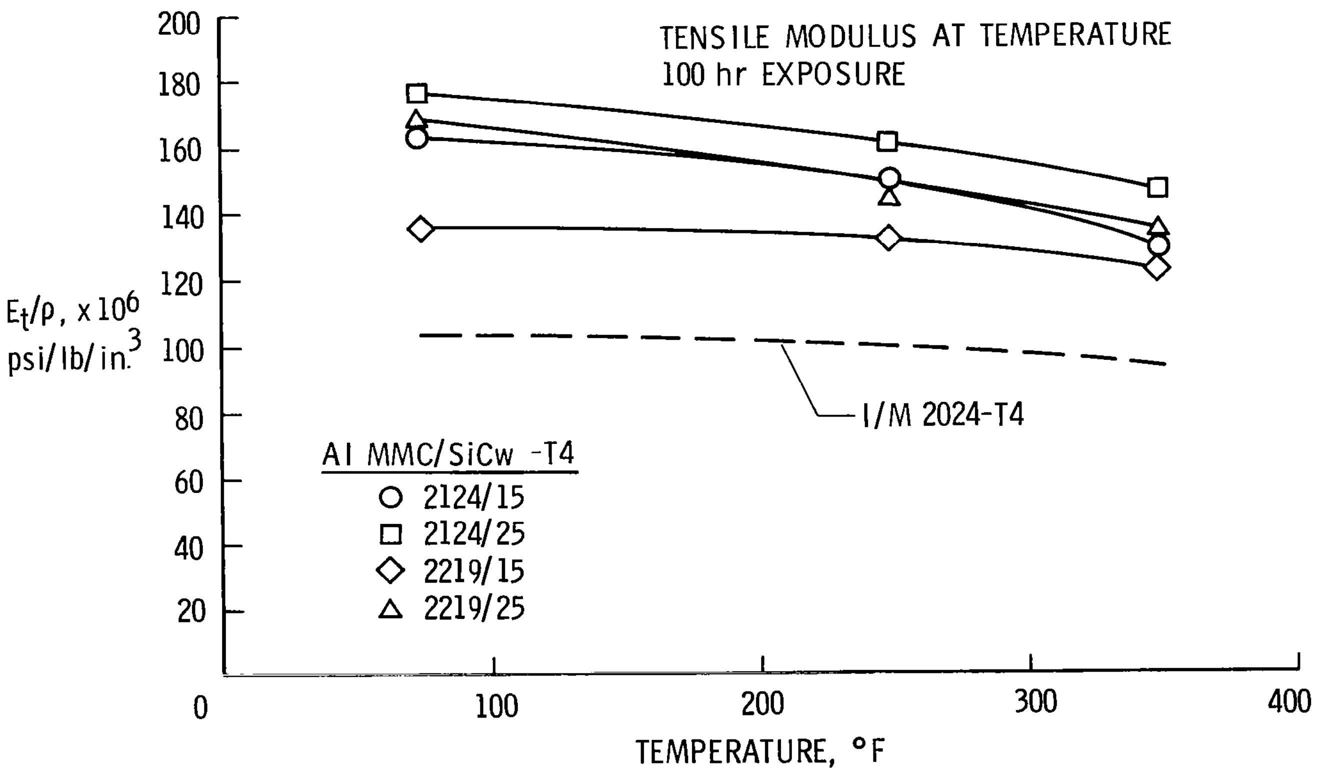


Figure 13

CONCLUSIONS

Based on this survey of advanced aluminum technology status and plans, the following can be concluded:

- o Powder metallurgy aluminum alloys can be synthesized with the required balance of properties that offer high potential for efficient aerospace structures for the 1990s and beyond
- o Future applications in nonaerospace industries are expected as the technology matures.
- o A comprehensive national long range program of research, development, and applications is underway
- o The NASA-LaRC contribution to that program concentrates on P/M 2000-series alloys and on those alloys as composite matrices reinforced with silicon carbide. The focus is on the understanding of chemistry/metallurgical/structure/thermomechanical processing/mechanical property relationships

REFERENCES

1. NMAB Committee on Powder Aluminum Alloys: "Rapidly Solidified (RS) Aluminum Alloys - Status and Prospects". National Materials Advisory Board Report No. 368, 1981.

2. Sakata, I. F.: "Systems Study of Transport Aircraft Incorporating Advanced Aluminum Alloys - Final Report". NASA CR-165820, January 1982.

3. Wald, G. G.: Supersonic Cruise Vehicle Technology Assessment Study of an Over/Under Engine Concept - Advanced Aluminum Alloy Evaluation. NASA CR-165675, May 1981.