ARTICLE NO. 79-0755R

C 80-089

00030
40002

Structural Aluminum Materials for the 1980's

R.F. Simenz* and M.K. Guess†
Lockheed-California Co., Burbank, Calif.

Developments in processing and alloying techniques have resulted in property improvements and increased potential application for advanced aluminum alloys in both subsonic and supersonic aircraft. Advanced aluminum alloys are a promising material in addition to the advanced composites and titanium alloys for current and future aircraft. Alloys receiving the bulk of attention for subsonic applications include the high strength corrosion-resistant 7050 alloy, the high-strength CT90, CT91, and 9051 powder alloys, and the aluminum-lithium alloys. Combinations of powdered alloys, aluminum-lithium, and mechanical alloying are being considered for high temperature supersonic applications.

Aluminum Alloys for Subsonic Aircraft

IMPROVEMENT in the strength/weight ratio of aircraft structural materials is a high priority goal in the aircraft industry. Development efforts to improve the strength of aluminum alloys also place emphasis on improving alloy durability characteristics including damage tolerance and corrosion resistance.[1]

Two aluminum alloys that are widely used in commercial transports are 2024 and 7075. The former is used primarily for components with high damage tolerance requirements such as fuselage skins, whereas 7075 sees extensive application for forgings as well as structures loaded principally in compression such as upper wing surfaces. These two materials have been mainstays in transport aircraft construction even though higher strength aluminum alloys have been available for many years. However, the higher strength alternate aluminum alloys usually have shortcomings in toughness or stress corrosion. 7178-T6 and 7079-T6 are notable examples of materials that have experienced service problems. 7075-T6 also has suffered from stress corrosion cracking (SCC) in certain applications, but overaging has been employed very successfully as a means to increase its SCC resistance in the transverse grain direction when required in a specific design application.

Properties and Metallurgical Relationships

A key goal has been to develop alloys with increased strength over 2024 and 7075 without lowering durability. A number of promising approaches have emerged as a result of progress in aluminum technology in the last 10 years. For example, gains in fracture toughness have been achieved by reducing impurities and controlling soluble phases and other features of macro- and microstructural morphology in conventionally processed ingot material.[2]

More specifically, toughness has been improved by control of particles associated with impurity elements such as iron or silicon which result in completely insoluble particles, and certain intermetallic compounds which are only partially soluble. Various investigations have shown that the size and distribution of such particles are important to toughness because the particles are easily fractured under stress and thus provide preferential crack paths.

Also, particles of Cr and Mn, which are added to control recrystallization, can lead to formation of microvoids adjacent to the particles and thus can have an adverse effect on toughness. Use of Zr in lieu of Cr or Mn has been found to provide better resistance to crack propagation.

The prime contributor to alloy strengthening and fracture behavior is of course the hardening precipitate particles composed of the major alloying elements. For example, in 7XXX alloys control of metalworking process, solution treatment, quench, and aging can be used to avoid adverse morphology such as grain boundary precipitate and wide precipitate-free zones which favor intergranular fracture and low toughness.

Alloy chemistry modifications, thermal mechanical treatments, powder metallurgy techniques, and rapid solidification rate (RSR) processes are additional means available in the development of higher strength, higher toughness aluminum alloys.

Current and Improved Aluminum Alloys

Figure 1 shows a comparison of candidate upper wing skin, plate product strength properties for a variety of high strength aluminum alloys. It is apparent that, with the exception of 7150, strength properties are only equal or somewhat lower than the baseline 7075-T6. However, in Fig. 2 the toughness and stress corrosion characteristics are compared showing the improvements that have been achieved in these properties.[3,4]

Exfoliation corrosion resistance is also an important property when structural durability is considered. Figure 3 indicates the relative behavior of these alloys when subjected to accelerated exfoliation testing.

Property Improvements in 7050

The clear superiority of 7050-T7E73 extrusions over 7075-T6 in fatigue crack growth and toughness is shown in Fig. 4. These curves are based on data from Ref. 5 and compare the two materials at equivalent tensile strength levels. The 7050 alloy material tested in this program illustrates what can be achieved through application of alloying principles and microstructural controls to improve toughness behavior.

Status of Advanced Aluminum Alloy Development for Subsonic Aircraft

Payoff Analysis

A recent in-depth design payoff analysis of a family of alloys considered the effect on airframe weight with assumed levels of improved properties.[6] In this analysis, airframes for two different types of aircraft were categorized by critical design condition and failure mode for each major component. The fraction of aircraft structural weight sized by each criterion was then readily determined. The results indicated that airframe weight reductions of 14.6 and 12.2% could be achieved in a carrier-based antisubmarine warfare patrol aircraft and wide-body transport, respectively, using the defined property level improvements in advanced aluminum

---

Presented as Paper 79-0755 at the AIAA/ASME/ASCE/AHS 20th Structures, Structural Dynamics, & Materials Conference, St. Louis, Mo., April 4-6, 1979; submitted May 7, 1979; revision received Nov. 15, 1979.

Index categories: Structural Materials; Materials, Properties of.

*Department Engineer, Materials and Processes.
†Research Specialist Senior.

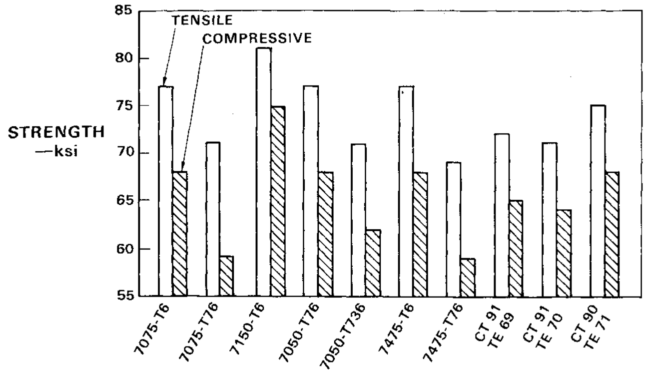

Fig. 1 Tentative design properties for 0.500 to 1.00 plate.

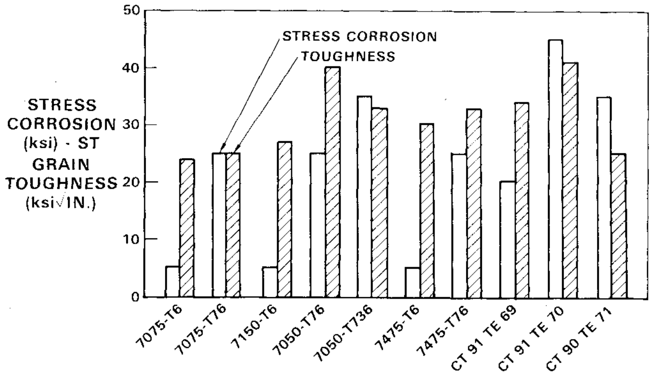

Fig. 2 Tentative design properties for 0.500 to 1.00 plate.

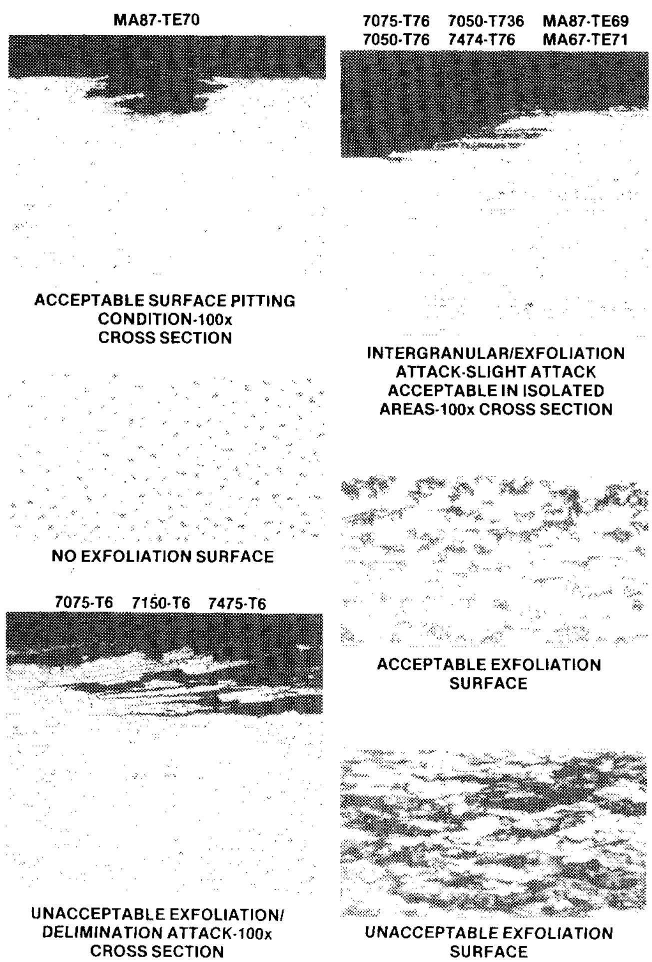

Fig. 3 Comparison of exfoliation resistance.

Table 1 Advanced aluminum alloy payoff analysis

Alloy type[a]	Weight reduction, % of structured weight: Carrier-based ASW patrol	Wide-body transport
20%,higher fatigue and da/dn	8.1	4.2
20%, higher or stiffness	3.6	3.6
20%, higher strength	2.3	2.5
Equivalent strength	0.6	1.9
Total	14.6	12.2

[a] All low density (approximately 10% less than baseline materials).

alloys. These predicted weight reductions are based on optimum combination of low density alloys with assumed 20% property improvements as shown in Table 1.

This preliminary analysis has been useful as a screening tool in providing guidance to advanced alloy development efforts. An improved material property sensitivity model currently is being developed for similar use. The improved model will extend the criteria categories and give consideration to items such as minimum gage, foreign object damage, nonoptimum factors, structural concept options, and secondary material properties. The use of advanced composites in conjunction with advanced aluminum must also be considered since it is likely that aircraft in the late 1980's will incorporate composite materials in primary structure on a production basis.

Aluminum-Lithium Alloys

The Al-Li system is receiving major attention because of its well-documented ability to produce significant increases in modulus combined with decreases in density.[7] However, ductility, toughness, and segregation have presented problems. New approaches are being investigated, including use of high purity lithium, RSR techniques, and control of microstructures by alloy addition and processing.

A wide range of alloy densities have been produced. Modulus of elasticity exceeding 14 *million* psi have been obtained by a number of investigators in lithium and nonlithium-bearing aluminum alloys. Rapid quenching is being employed to decrease grain size, increase solid solubility, and eliminate segregated phases. In the case of Al-Li alloys, attempts are also being made to use alloying elements to produce a fine dispersion of nondeformable particles to prevent localization of slip and thus improve toughness as well as stabilize the fine grain size produced by RSR.

Various RSR particulate manufacturing concepts and gas atomization powder manufacturing concepts are being refined and intense investigation is under way to establish consolidation and processing parameters and improve safety for handling fine particles.

Some typical heat treat response data obtained at Lockheed on developmental lithium-containing alloys are shown in Fig. 5. These materials were prepared by RSR technique followed by compaction and extrusion. A density of 0.091 was obtained in the Al-2.7 Li alloy and the tensile modulus was approximately 12 million psi which represents an increase of over 30% in specific stiffness compared to current aluminum alloys. Additional effort in this particular Lockheed study is under way to obtain improved ductility and toughness, particularly in the higher strength heat treat conditions.

Future Advanced Alloy Development Needs

The development cycle required for low risk introduction of new aluminum alloys into primary structure applications typically can take 6-8 years. This much time is required to assure that a satisfactory data base is established covering scale up, mill processing, fabrication, design allowables,

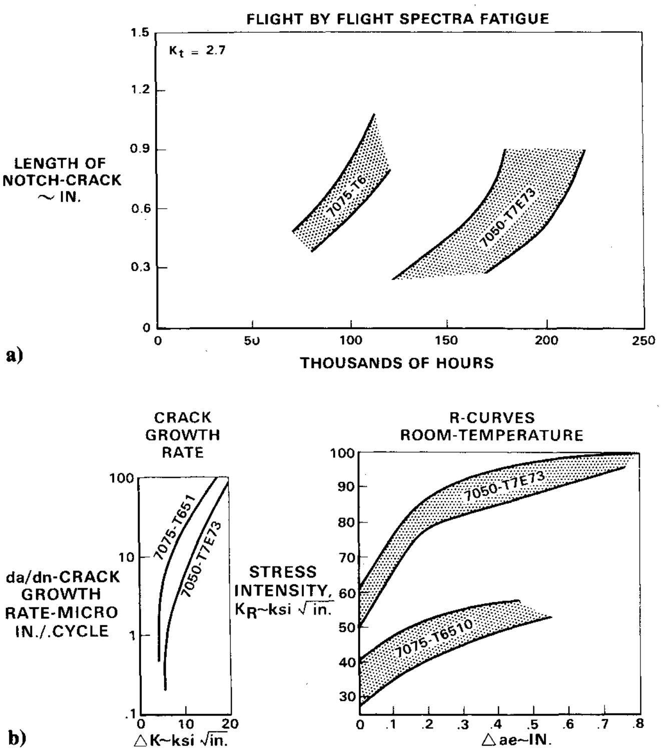

Fig. 4 Fatigue, crack growth, and *R* curve properties of 7075-T6 and 7050-T7E73.

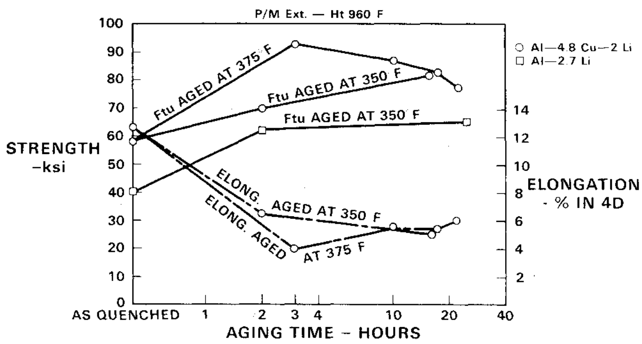

Fig. 5 Effect of aging time on properties of Al-4.8-Cu-2Li and Al-2.7 Li.

environmental behavior, and joint and component testing. Thus, if current efforts on advanced aluminum alloys are successful in achieving the properties projected above, a new family of structural aluminum alloys could be available in the late 1980's.

These alloys should offer the potential for substantial weight reduction compared to today's materials. However, it will take substantial funding and a major cooperative effort among the aerospace industry, the aluminum producers, the research laboratories, and government agencies to complete the development and establish the appropriate data base for these materials.

Aluminum Alloys for Supersonic Applications

Precipitation hardening aluminum alloys have been widely used in the aerospace industry over the past 35 years because of their relatively low raw material and fabrication costs and the ability to develop satisfactory specific strengths for subsonic applications. For sustained use in the Mach 2.0 to 2.7 supersonic range, however, conventional aluminum alloys have presented some unacceptable drawbacks. First, conventional aluminum alloys are not as structurally efficient as titanium for many structural applications in a Mach 2.0 to 2.2

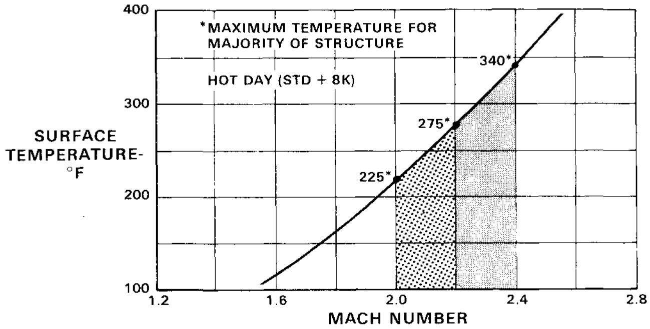

Fig. 6 Temperature vs Mach number for high temperature alloys.

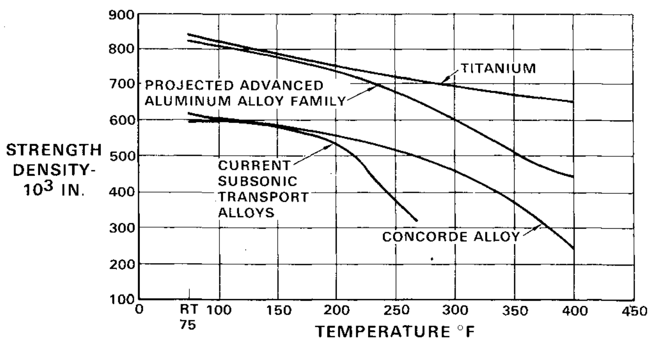

Fig. 7 Advanced aluminum alloys for high temperature applications.

transport, and secondly, development of a high strength aluminum alloy having good thermal stability at temperatures created above Mach 2.2 speeds have been lacking.[8] As a result of these limitations, airframe designers have been forced to accept reductions in performance or look for alternate materials to be used in structures for supersonic transport use.

Background

NASA funded studies conducted by private airframe and engine manufacturers including Lockheed, Boeing, McDonnell Douglas, General Electric, and Pratt & Whitney have indicated that a supersonic transport aircraft operating above Mach 2.2 would probably be fabricated from approximately 70% titanium. The reason for this is the good stability of titanium at temperatures in the 300 to 500°F operating range where a Mach 2.2+ transport would operate (see Fig. 6). When operating below Mach 2.2, however, supersonic transport structures are exposed to temperatures in the range of 225 to 275°F. At these temperatures aluminum could be incorporated in the airframe structure. The French and British incorporated a considerable amount of aluminum in the Concorde which cruises at a speed of Mach 2.02; however, the alloy used has a strength/density ratio which is not competitive with titanium alloys (see Fig. 7). Currently, conventional aluminum alloys are not competitive with titanium because of their lower strength and temperature resistance. However, advances in aluminum processing and alloying technologies have shown a potential for eliminating these strength and temperature barriers. The desired goal for projected advanced aluminum alloys is also shown in Fig. 7.

The Air Force is funding research and development on structural aluminum alloys that will retain their yield strength after exposure to 450°F for 10,000 h. In the commercial field, the Lockheed-California Co. under NASA sponsorship is initiating studies for advanced aluminum alloys capable of good strength retention in the temperature range of 250 to 350°F. These temperatures will be encountered at the Mach 2.0 to 2.4 speed range for periods up to 100,000 h in commercial supersonic transports under current study. Such studies suggest that commercial supersonic flight in the Mach 2.0 to 2.2 range may be more productive than flight at Mach

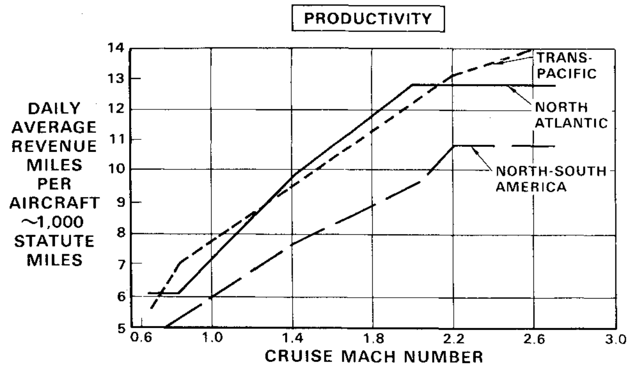

Fig. 8 Cruise speed advantages.

2.7. Room temperature properties must be unaffected by elevated temperature exposure and elevated temperature properties must be equal to or greater than 80% of room temperature properties.

New Materials and Cruise Speed Developments

Material Developments

According to the Aluminum Co. of America (ALCOA) a considerable effort over the course of many years has been expended in attempts to improve the elevated temperature performance of aluminum alloys. One of the most promising approaches studied by ALCOA relies upon creating a fine dispersion of a second phase through rapid solidification and maintaining it through subsequent consolidation and processing into final product forms.[9] Materials of this type have been produced which exhibit thermal stability but their mechanical properties are unacceptably low and, thus, have not gained widespread use. Recent work at ALCOA Laboratories has employed high velocity gas atomization to form particulates. This process has demonstrated that through proper control of alloying, particulate cooling rate, consolidation temperature, and total deformation during consolidation, aluminum alloy products that develop very high room and elevated temperature tensile properties can be fabricated. According to ALCOA, this work was limited in scope, however, and a wide variety of alloying additions and fabricating conditions remain unexplored.

Along a different front, the International Nickel Co. (INCO) employing the newly developed process of mechanical alloying has demonstrated a capability for coping with the problems of developing a high strength, temperature resistant aluminum alloy. Mechanical alloying is a technique for producing composite metal powders with controlled fine microstructures. It occurs by the fracturing and rewelding of a mixture of powder particles during milling via a highly energetic ball charge. The process takes place entirely in the solid state. Typically the process is carried out in high energy stirred ball mills.[10,11]

This process was developed by INCO for the manufacture of dispersion strengthened alloys and it shows considerable promise for developing the required properties in aluminum. Through the mechanical alloying process, homogeneous alloys strengthened by oxide dispersions as well as additions of soluble and insoluble metallic ingredients can be produced. The materials produced by the process display the exceptionally fine and stable types of microstructures which are needed to provide the desired improvement in elevated temperature properties of aluminum alloys. Commercialization of the process is now well under way.

Cruise Speed Developments

A comparison was made of airplane productivity and utilization levels for four supersonic commercial aircraft.[12] The productivity and utilization levels were based on 1995 passenger demand forecasts; the cruise speed component was the only influence on schedules. Productivity-speed relationships were determined for three discrete route systems: North Atlantic, transpacific, and North-South America. All three route systems show airplane productivity practically doubling between cruise speeds of Mach 0.82 and 2.0. Above Mach 2.0, further productivity gains are a function of the particular route system. The route systems with longer cruise distances are able to take advantage of cruise speeds higher than Mach 2.0; however, a weighted average of

Table 2 High temperature aluminum alloy environmental requirements for supersonic transport

Property	Remarks
Structural life	100,000 h total, 70,000 h at 275°F
Stability	Room temperature properties unaffected by elevated temperature exposure
Elevated temperature properties	Greater than 80% of room temperatures
Creep strength	Greater than 18 ksi for 0.1% creep in 70,000 h
Corrosion resistance	Equal to or greater than superior corrosion resistance being demonstrated by Lockheed L-1011 aircraft

Table 3 Damage tolerant fatigue resistant alloy goals

	Aluminum reference			Aluminum goals	
	Concorde	Commercial jet	Ti 6-4 base	Properties	Improvement
Properties	2618-T6	2024-T3	$F_n = F\frac{\rho \mathrm{Al}}{\rho \mathrm{Ti}}$		
Strength, ksi					
F_{tu}	62	62	84	68	10% > 2618
F_{cy}	56	39	82	62	10% > 2618
Fatigue					
F_{max}, ksi $n = 10^5$	19	20	30	30	50% > 2024-T3
ΔK, ksi$\sqrt{\text{in.}}$ at $R = 0.1$, $da/dn = 10^{-6}$	5.6	6.0	5.6	7.2	20% > 2024-T3
Other					
K_{app}, ksi$\sqrt{\text{in.}}$	70	80-100	81	81	16% > 2618
K_{IC}, ksi $\sqrt{\text{in.}}$	26	30	44	30	16% > 2618
E, msi	10.9	10.7	10.0	10.7	~2024

Table 4 High strength alloy goals

Properties	Aluminum reference 2618-T6	Ti 6-4 base $F_n = F\frac{\rho Al}{\rho Ti}$	Aluminum goals Properties	Improvement
Strength, ksi				
F_{tu}	62	84	62	~2618
F_{cy}	56	82	55	~2618
Fatigue				
F_{max} $K_t=3$, $R=0.1$ $n=10^5$	19	30	19	~2618
ΔK,ksi$\sqrt{\text{in.}}$ at $R=0.1$. $da/dn=10^{-6}$	5.6	5.6	5.6	~2618
Other				
K_{app},ksi$\sqrt{\text{in.}}$	70	81	60	~7075-T6
K_{IC},ksi$\sqrt{\text{in.}}$	26	44	26	~7075-T6
E/ρ,msi/lb/in.^{3}	10.9	10.0	13.1	25% > 7075-T6

Table 5 High stiffness alloy goals

	Aluminum reference			Aluminum goals	
	Concorde	Commercial jets	Ti 6-4 base	Properties	Improvement
Properties	2618-T6	7075-T6	$F_n = F\frac{\rho Al}{\rho Ti}$	$\rho \simeq 0.1$	
Strength, ksi					
F_{tu}	62	77	84	84	10% > 7075-T6
F_{cy}	56	68	82	82	10% > 7075-T6
Fatigue					
F_{max},ksi $n=10^5$	19	20	30	23	20% > 2618
K,ksi$\sqrt{\text{in.}}$ at $R=0.1$, $da/dn=10^{-6}$	5.6	5.6	5.6	6.2	10% > 7075-T6
Other					
K_{app},ksi$\sqrt{\text{in.}}$	70	60	81	60	~7075-T6
K_{IC},ksi$\sqrt{\text{in.}}$	26	26	44	26	~7075-T6
E,msi	10.9	10.5	10.0	10.5	~7075-T6

Table 6 Low density alloy goals

Properties	Aluminum reference 2618-T6	Ti 6-4 base $F_n = Fx\frac{\rho Al}{\rho Ti}$	Aluminum goals Properties	Improvement
Strength, ksi				
F_{tu}	62	84	62	~2618
F_{cy}	56	82	55	~2618
Fatigue				
F_{max} $K_t=3$, $R=0.1$ $N=10^5$	19	30	~2618	~2618
ΔK,ksi$\sqrt{\text{in.}}$ at $R=0.1$. $da/dn=10^{-6}$	5.6	5.6	5.6	~2618
Other				
K_{app},ksi$\sqrt{\text{in.}}$	70	81	60	~7075-T6
E,msi	10.9	10.0	12.5	15% 2618
Density, lb/in.^{3}	0.1	...	0.09	10% 2618

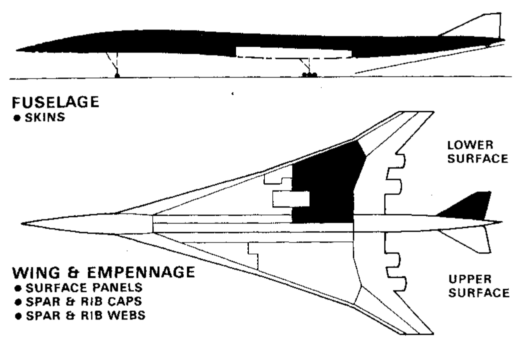

Fig. 9 Damage tolerant fatigue resistant alloy applications.

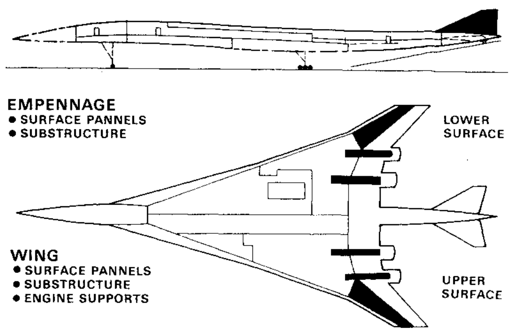

Fig. 11 High stiffness alloy applications.

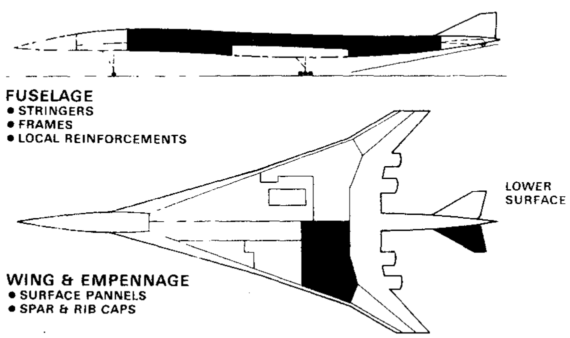

Fig. 10 High strength alloy applications.

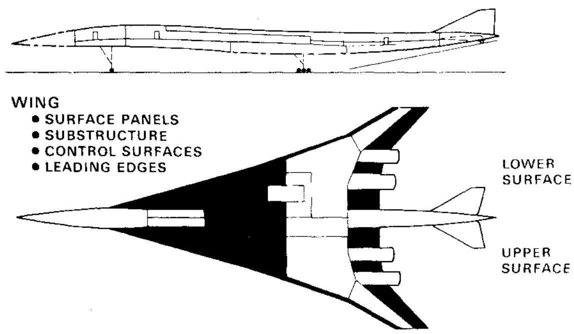

Fig. 12 Low density alloy applications.

all three route systems shows only an additional 10% increase in productivity of the Mach 2.7 aircraft over the Mach 2.0 aircraft and at Mach 2.2 only the transpacific route system shows a productivity increase (see Fig. 8).

These noted developments in new materials technology and cruise speed studies indicate the potential for economic operation of supersonic transports in the Mach 2.0 to 2.2 range. Therefore the Lockheed-California Co. with the aid of NASA funding has initiated feasibility studies to investigate advanced high temperature aluminum alloys in conjunction with ALCOA and INCO.

Requirements for New Materials

Discussions between Lockheed, ALCOA, and INCO indicated that development of a single aluminum alloy with all of the properties of titanium was not a practical prospect. However, since only a limited number of properties are critical for any given part of an aircraft structure, it was agreed that a family of aluminum alloys could readily compete with titanium structures. With this fact in mind, four sets of property goals have been established for improved aluminum alloys. These goals represent structural equivalence with titanium alloys in the properties that are critical for a given application. The four alloys being considered are: 1) a high strength alloy, 2) a damage tolerant alloy, 3) a high stiffness alloy, and 4) a minimum gage or low density alloy. The environmental criteria requirements for the alloys are shown in Table 2. A total airframe life expectancy of 100,000 h with 70,000 of these hours at 275°F will be needed. This requirement assumes an aircraft with a service life of 30,000 flights or more which would make supersonic commercial aircraft service life compatible with the latest subsonic transport objectives. It is also assumed that the four alloys must withstand a sustained load of 18,000 psi at 275°F for 70,000 h with less than 0.1% creep. Corrosion resistance equal to or greater than the superior corrosion resistance presently being demonstrated by Lockheed's L-1011 subsonic commercial transport is also a requisite.

Mechanical property goals for the family of alloys were established by making the primary property equivalent to that for 6Al-4V titanium. Tables 3 to 6 show these property goals along with existing Concorde and commercial subsonic jet properties and the increase in properties required to make the alloys equivalent to titanium. In some cases secondary

Table 7 Cost comparison of aluminum vs titanium for SCV

Item	Baseline conventional titanium structure	Advanced titanium fabrication technology	Conventional aluminum structure	Advanced al. material conventional fabrication	Advanced al. and fabrication techniques
Recurring structure cost,[a]	32,159	24,914	23,588	20,711	18,640
Total recurring cost, $[a]	81,253	69,374	71,987	62,910	60,039
Savings per aircraft, $	...	11,879	9,266	18,343	21,214
Saving, %	...	15	11	22	26

[a] Cumulative average for 300 aircraft in 1976 dollars ($1000's).

properties have also been increased. The increases were made after discussions with material developers indicated the higher goals could probably be met without sacrificing the primary goals, thus providing added material capabilities where secondary properties play a major role in design requirements. To facilitate comparison, the Ti6A1-4V properties shown in these figures have been normalized by multiplying by the ratio of the density of aluminum to that of titanium.

Potential Applications

Potential applications for the family of alloys are shown in Figs. 9-12. The damage tolerant fatigue resistant alloys would be used for fuselage skins and wing/empennage lower surface panels, spars, and ribs. High strength alloys would include fuselage stringers and frames and upper surface wing/empennage panels, spars, and ribs. High stiffness applications shown in Fig. 11 cover the empennage surface panels and substructure, the wing tip surface panels, and the engine supports. Low density alloy applications cover minimum gage structures such as leading edges, trailing edges, and forward wing surface panels.

Producibility/Cost Benefits

The primary payoff to be gained from the use of advanced aluminum alloys relate to the production economics obtained through the use of aluminum instead of titanium. In making a producibility assessment of the two materials Lockheed has concluded that aluminum provides the following benefits:

1) High volume production equipment and facilities available.

2) Standard low cost fabrication procedures established.

3) No special personnel training required.

4) Perishable tool expenditures lower than for competitive metallic alloys.

5) Equipment maintenance costs lower than for competitive metallic alloys.

More detailed production cost comparisons of aluminum and titanium for supersonic cruise vehicle (SCV) studies are shown in Table 7. Studies were made comparing a baseline titanium SCV aircraft using conventional producibility methods with titanium structures using advanced methods such as superplastic forming and diffusion bonding. Conventional aluminum alloy structures such as that used for the Concorde and advanced aluminum alloy structures such as the family of alloys discussed here were compared with the titanium alloys. These studies show potential producibility/cost advantages of up to 26% for advanced aluminum alloys.

Summary

Analytical studies have shown that the projected advanced aluminum alloys offer substantial weight reduction payoffs compared to current aluminum alloys for both subsonic and supersonic aircraft. Thus the projected advanced aluminum materials warrant continued consideration for a wide variety of aircraft structural applications. Development studies to date have made significant progress toward achieving new elevated temperature resistant alloys of aluminum, as well as more structurally efficient and damage tolerant alloys for subsonic aircraft applications. Supersonic cruise vehicle design studies to establish aluminum alloy structural concepts that maximize structural efficiency are underway, and studies to assess further related cost reduction benefits are continuing.

References

[1] Stauffer, W.A., "Future Trends in Aircraft," AIAA Paper 78-465, AIAA/ASME 19th Structures, Structural Dynamics, and Matenals Conference, Bethesada, Md., April 1978.

[2] Staley, J.T., "Aluminum Alloy and Process Developments for Aerospace," *Metals Engineering Quarterly*, May 1976.

[3] Hyatt, M.V., Quist, W.E., and Quinlivan, J.T., "Improved Aluminum Alloys for Airplane Applications," *Metal Progress*, March 1977.

[4] Lovell, D.T., and Disotell, M.A., "Structural Material Trends in Commercial Aircraft," Paper 78-1552, AIAA Conference on Air Transportation, Los Angeles, Calif., Aug. 1978.

[5] Brodie, R.W., and Bakow, L., "Comparison of Engineering Properties of 7050 and 7075 Extrusions," NADC-76269-30, Feb. 1978.

[6] Lewis, R.E., Webster, D., and Palmer, I.G., "A Feasibility Study for Development of Structural Aluminum Alloys from RSR Powders for Aerospace Structural Applications," AFM-TR-102, July 1978.

[7] Sanders, T.H., and Balmuth, E.S., "Aluminum-Lithium Alloys: Low Density and High Stiffness," *Metal Progress*, March 1978.

[8] "Studies of the Impact of Advanced Technologies Applied to Supersonic Transport Aircraft," Vol. II, First Year Summary Report, Douglas MDC 54394, Sept. 1973, prepared under Contract NAS1-11939 for NASA Langley Research Center, Hampton, Va.

[9] Sawtell, R.R., et al., "Elevated Temperature Al. Alloy Development," ALCOA Laboratories, March 28, 1978.

[10] Benjamin, J.S., "Mechanical Alloying," *Scientific American*, Vol. 234, May 1976, p. 40.

[11] Benjamin, J.S. and Bomford, M.J., "Dispersion-Strengthened Aluminum Made by Mechanical Alloying," *Metallurgical Transactions*. Vol. 8A, Aug. 1977, p. 1301.

[12] Bond, E.Q., et al. "Impact of Cruise Speed on Productivity of SST's," AIAA Paper 79-0231, AIAA 17th Aerospace Sciences Meeting, New Orleans, La., Jan. 15-17, 1979.