Elevated Temperature Aluminum Alloys for Advanced Fighter Aircraft

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Elevated temperature aluminum alloys are being developed for aircraft structural applications in the 300–600°F temperature range. Material properties of various alloy systems and product forms display excellent room and elevated temperature strength, fracture toughness, and corrosion resistance. These materials are considered for applications in the aft fuselage of an Advanced Tactical Fighter. Design trade studies were conducted for a center keel beam structure between the engine compartments. Results show potential weight and cost savings of 12.8 and 46.5%, respectively, for a structure fabricated from elevated temperature aluminum alloys as opposed to titanium alloys. Additional weight and cost savings can be achieved by using hot molded metal matrix composite Al/SiC$_f$ beam caps.

Nomenclature

b	= stiffener or frame spacing, in.
D	= fastener diameter, in.
E	= modulus of elasticity, 10^6 psi
E_L	= modulus of elasticity in L direction, 10^6 psi
E_{LT}	= modulus of elasticity in LT direction, 10^6 psi
F_a	= axial load, lb
F_{br}	= bearing stress, psi
G	= shear modulus of elasticity, 10^6 psi
G_{LT}	= shear modulus of elasticity in LT direction, 10^6 psi
H	= height, in.
I	= moment of inertia, in.^{4}
L	= length, in.
N	= axial load per unit width, lb/in.
P	= pressure, psi
q	= shear stress per unit width, lb/in.
t	= material thickness, in.
W	= width, in.
γ_{LT}	= allowable shear strain in LT direction, in./in.
ϵ_L	= allowable strain in L direction, in./in.
ϵ_{LT}	= allowable strain in LT direction, in./in.
ν_{LT}	= Poisson's ratio in LT direction

Introduction

MEETING weight and cost objectives for aerospace weapon systems, such as the Advanced Tactical Fighter (ATF), is a major challenge in materials development. These advanced designs must use newly emerging materials that offer significant improvements in properties while simultaneously demonstrating lower acquisition and life cycle costs. Conventional aluminum and aluminum-lithium alloys are not weight and cost effective at elevated temperatures because of reductions in strength and stiffness. Advanced elevated temperature aluminum alloys have the potential of achieving significant weight and cost savings as a replacement for titanium alloys in the 300–600°F temperature range.

In the late 1970s, it was recognized that elevated temperature aluminum alloys would reduce weight and cost for airframe applications on supersonic aircraft and for engine-heated structure of subsonic aircraft. Using state-of-the-art rapid solidification techniques, unique powder metallurgy (PM) alloys were developed, including Al-Fe-Ce by the Aluminum Company of America (Alcoa), Al-Fe-V-Si by Allied-Signal, Inc., and Al-Fe-Mo by Pratt & Whitney. Both alloy and process development studies have been funded by the U.S. Air Force to establish the potential benefits of elevated temperature aluminum alloys in airframe and engine-heated structures.[1,2] The material suppliers have scaled-up to produce billets in excess of 500 lb. These materials are becoming available in sheet, plate, forging, and extruded product forms for aircraft structural applications.

This paper presents materials property data on various elevated temperature aluminum alloys in sheet, extrusion, and forging product forms. A design trade study was conducted for a center keel beam component in the aft fuselage structure for a generic advanced tactical fighter. Weight and cost comparisons were made for this application using elevated temperature aluminum alloys, metal matrix composite Al/SiC$_f$, and graphite/polyimide composite in lieu of titanium.

Materials Development and Characterization

Selection Criteria

A number of new aluminum alloy systems have been formulated and characterized by the major producers to extend the elevated temperature performance. The development and application of these emerging elevated temperature aluminum alloys is directed toward the selective replacement of conventional titanium alloys up to 600°F. The evaluation and selection of elevated temperature aluminum materials was performed on the center keel beam structure to determine the

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most efficient candidates. The proposed structural arrangement and materials selection thereby offers the optimum combination for weight and cost savings over the baseline titanium structure.

The materials selection process consisted of two distinct tasks. In the initial task, specific alloys were assessed with respect to level of maturity for each product form, such as sheet, plate, extrusions, and forgings. The influence of processing variables leads to inherent differences as a function of both product form and alloy content. In the second task, relative trade-offs in terms of material behavior and availability were conducted for the candidate materials. The selection approach employed for the application of elevated temperature aluminum alloys consisted of the following criteria: 1) material quality, 2) availability, and 3) material cost. Each of these factors is important in the successful transition of materials technology to advanced weapons system application. Multiple alloy compositions and product forms were considered in cases where the candidate materials appeared to exhibit comparable material behavior and cost.

Material quality was evaluated on both a macroscopic and microscopic level. Based on recent Lockheed Aeronautical Systems Company (LASC-Burbank) experience in the characterization of elevated temperature alloys, the most significant discriminator in establishing material quality has been fracture toughness and strength. For many years the material producers have labored to understand and improve the fracture toughness of this class of aluminum alloys. However, it was not until the completion of the U.S. Air Force contract (see Ref. 1) that toughness improvements were clearly demonstrated. Fracture toughness properties are therefore considered equal in overall importance to elevated temperature strength retention in providing assurances to material quality suitable for airframe structural applications. The primary measure used by LASC-Burbank in screening a particular alloy composition and product form was room and elevated temperature tension and fracture toughness properties. Depending on the results of these screening tests, additional mechanical properties were determined, such as compression, postexposure thermal stability, constant amplitude notched fatigue, fatigue crack propagation, and corrosion resistance.

The availability of scaled-up billets for these PM aluminum alloys is a critical milestone in the demonstration of material maturity for airframe applications. Larger billet sizes are mandatory for satisfying the product size requirements in sheet and plate for fighter aircraft fuselage structure. Additionally, scaled-up billet sizes contribute to improved economics for the fabrication and utilization of elevated temperature aluminum alloys. Billet sizes ranging from 500 to 750 lbs have been fabricated for use in the programs cited in Refs. 2 and 3. Standard aluminum sheet and light gauge plate (48 in. wide × 96 in. long) in the elevated temperature aluminum alloy compositions are amenable to fabrication from these scaled-up billets.

The cost of candidate elevated temperature aluminum alloys was estimated and used as a selection criteria. Although current costs of these alloy products are relatively high due to the limited size of the fabrication base, projected costs are judged to be very competitive with alternative high-performance material systems. Cost projections, based on anticipated production rates and billet sizes, were used as a tool in selecting the candidate elevated temperature aluminum alloys.

Candidate Material Systems

Three elevated temperature aluminum alloy systems were extensively characterized by LASC-Burbank in a series of U.S. Air Force funded development programs. The evaluations provided a basis for identifying specific alloy compositions with optimum property combinations as a function of product form. The alloy systems selected for comparison include Al-Fe-Ce, Al-Fe-V-Si, and Al-Fe-Mo-V. The product forms and densities of the elevated temperature aluminum alloys under investigation are shown in Table 1. Alloy chemistries are also listed in weight percent solute and represent nominal compositions for each alloy system. The selection of individual alloy compositions and product forms within a system was based on discussions with the material producers. Direction with respect to target property levels was provided by LASC-Burbank. Product forms were chosen for evaluation based on anticipated use in the aft fuselage section of a fighter aircraft structure. For example, thin extruded shapes typical of frame, stiffener, and cap-type applications were assessed in the material selection decisions.

Material Properties

Property results obtained by LASC-Burbank were supplemented, as necessary, by information furnished by the individual material producers. All material supplied to LASC-Burbank for test and evaluation purposes corresponds to the as-fabricated condition. Testing was conducted according to established American Society of Testing Materials (ASTM) procedures and analysis methodology. A summary of the results contributing to the selection of each product form is given in the following sections.

Flat Rolled Sheet and Plate Products

The average longitudinal and transverse room temperature tension properties for FVS0812, FVS1212, and Al-8Fe-2Mo-1V sheet are shown in Fig. 1. Properties for CZ42 sheet (Al-7.1Fe-6.1Ce) obtained in the program cited in Ref. 2 are also shown for purposes of comparison. The highest strength

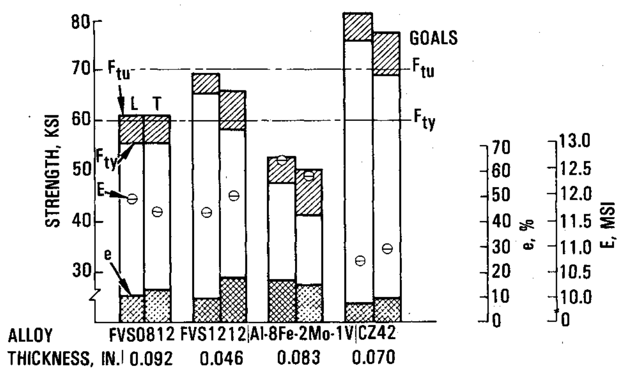

Fig. 1 Typical room temperature tension properties of elevated temperature aluminum sheet.

Table 1 Density of candidate elevated temperature aluminum alloys

Elevated temperature PM aluminum alloy	Measured density, lb/in.^{3}	Product forms evaluated
Al-7.1Fe-6.0Ce (CZ42)	0.106	S, E, F[a]
Al-8.0Fe-4.0Ce (CU78)	0.107	E
Al-8.5Fe-1.3V-1.7Si (FVS0812)	0.106	S, E, F
Al-11.7-Fe-1.15V-2.4Si (FVS1212)	0.109	S
Al-8Fe-2Mo-1V	0.106	S, E, F

[a]S = sheet; E = extrusion; F = forging.

of the four alloy compositions was obtained for CZ42 sheet material. Tension ultimate and yield strength properties were approximately 10–15 ksi above the target goal levels. Ductility of the CZ42 alloy was also shown to be satisfactory, with values ranging from 5.0 to 8.5%. The transverse properties were slightly lower than in the longitudinal grain direction, although somewhat improved ductility is observed in this direction. The CZ42 sheet results represent a vintage of processing that does not include the recent implementation of measures to improve overall toughness properties.

The Al-Fe-V-Si alloy series demonstrated generally lower strength and improved ductility compared to the CZ42 sheet. The higher strength FVS1212 alloy composition exceeded the yield strength goal and was approximately 2 ksi below the ultimate strength goal. As observed in the CZ42 alloys, adequate ductility values were typical of both the longitudinal and transverse grain directions. The lower solute FVS0812 alloy was 4–8 ksi lower in strength than the FVS1212 alloy. Elastic modulus values measured from the load vs displacement curves were slightly higher than characteristic of the CZ42 alloy. Higher modulus values were obtained for the Al-Fe-V-Si system, particularly for the FVS1212 alloy. It is anticipated that the high-volume fraction of primary α silicide strengthening phases in this alloy contribute to significantly improved modulus values compared to FVS0812. Additional precision elastic modulus measurements are required to accurately determine the appropriate values for each alloy system.

The Al-Fe-Mo-V sheet, processed from a 1300-lb billet, exhibited significantly lower strength than the other two alloy systems. Both tension ultimate and yield strength values were 12–15 ksi below the established goal properties. Processing difficulties encountered in the prolonged thermal soaking of this large billet may have precluded the attainment of adequate strength properties. Elastic modulus properties were reported to be considerably higher than either the CZ42 or FVS type alloys, with values ranging from 12.4 to 12.7 msi.

R-curve fracture toughness tests were conducted on the four alloys using compact tension (CT) specimens. Small test specimens were employed, using a W dimension of 1.8 in. due to the limited sheet material availability. The results of the fracture toughness tests vs yield strength are plotted in Fig. 2. As shown in the figure, the CZ42 sheet material is the only candidate alloy that meets the strength and toughness requirements. Center crack tension (CCT) panel tests on 8.0-in.-wide specimens conducted by LASC-Burbank indicate that K_{app} fracture toughness levels range from approximately 55.0 to 82.0 ksi-in.$^{1/2}$ for CZ42 sheet. This combination of toughness and strength for CZ42 sheet is similar to conventional high-strength 7075-T6 aluminum alloy sheet.

The fracture toughness for the FVS0812 alloy met the target goals at slightly lower overall strengths. The FVS1212 alloy exceeded the strength goal, but the toughness indications were only 42.0 ksi-in.$^{1/2}$. However, the small size of the compact tension specimens may be contributing to artificially low fracture toughness values, as evidenced by the Al-Fe-Mo-V results. The CZ42 alloy demonstrated the best combination of tensile strength and fracture toughness properties in sheet products. Sheet and plate products fabricated from scaled-up billets of approximately 750 lb are currently under evaluation to establish material design properties. In an effort to minimize the risk of billet scale-up, the FVS0812 alloy was also selected for development in sheet and plate products in the program cited in Ref. 3.

Extruded Products

The average room temperature tension properties for FVS0812, Al-8Fe-2Mo-1V, CZ42, and Al-8Fe-4Ce (CU78) extrusions are shown in Fig. 3. Results provided by Alcoa on CU78 extrusions were used for these comparisons due to the lack of properties data on thick section CZ42 extrusion representative of the improved toughness processing treatments. Data for the CU78 alloy extrusions is believed to be comparable to the properties of the CZ42 alloy. Mechanical property characterizations were conducted on thick (0.75–1.00 in.) and thin (0.10 in.) extruded shapes. Applications in the keel beam structural components have been shown to involve primarily thin extrusion sections. However, thicker products were evaluated to provide an indication of the fracture toughness properties in this product form.

The FVS0812 extrusions met the yield strength goal and were only 1–2 ksi below the required ultimate strength. Approximately 5–10 ksi higher strengths were obtained for these extrusions compared to the Al-Fe-Ce type alloys. Elastic modulus values for the FVS0812 extrusions were in good agreement with reported values from Allied and were comparable to CU78 extruded products at room temperature. The strength properties of the Al-Fe-Mo system varied considerably with processing history and billet size. Extruded pipe, produced from a 1000-lb billet, exhibited much lower strengths than extrusions fabricated from 100-lb billets. All of the extruded shapes demonstrated satisfactory tensile ductility with values typically ranging from 9 to 10%.

Plane strain fracture toughness tests were conducted on the thicker section extrusions, and plane stress R-curve fracture toughness tests were performed on the thin extruded shapes. The results of the toughness tests are plotted as a function of tension yield strength in Fig. 4. The FVS0812 alloy is the only extrusion to satisfy both the yield strength and fracture tough-

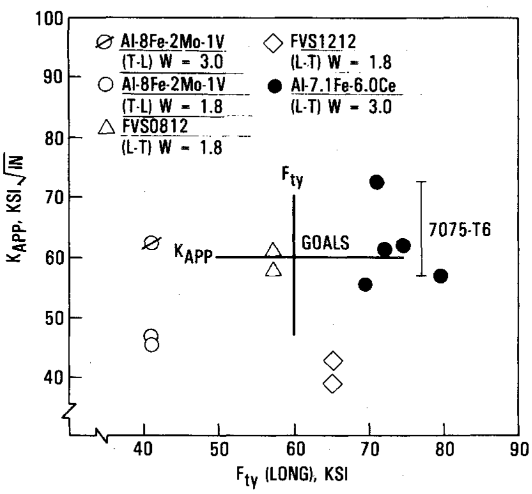

Fig. 2 Fracture toughness vs yield strength for elevated temperature aluminum sheet (0.090 in. thick).

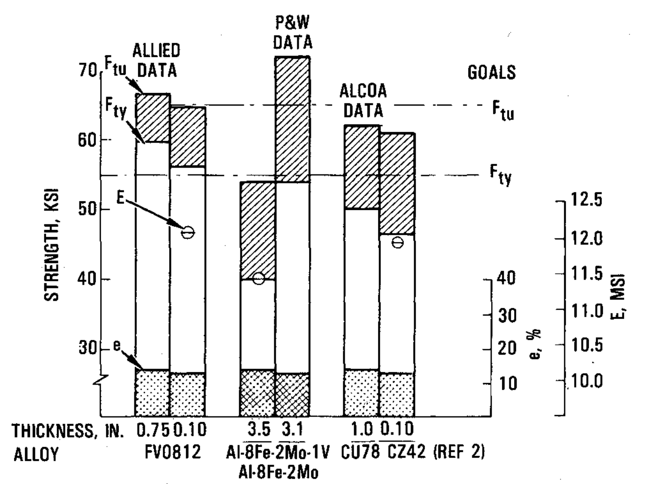

Fig. 3 Typical room temperature tension properties of elevated temperature aluminum extrusions.

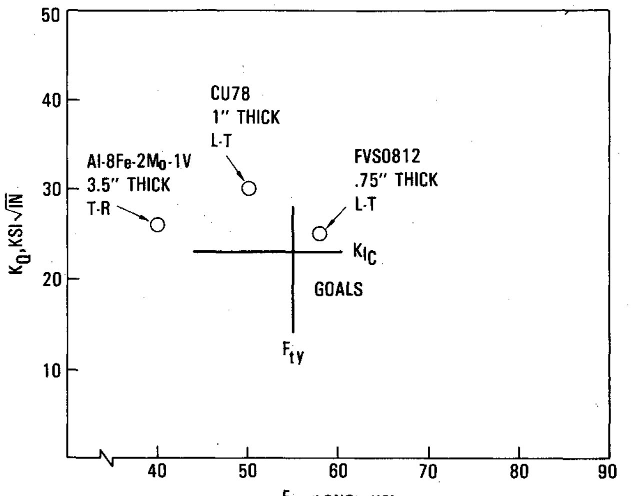

Fig. 4 Fracture toughness vs yield strength for elevated temperature aluminum extrusions.[2]

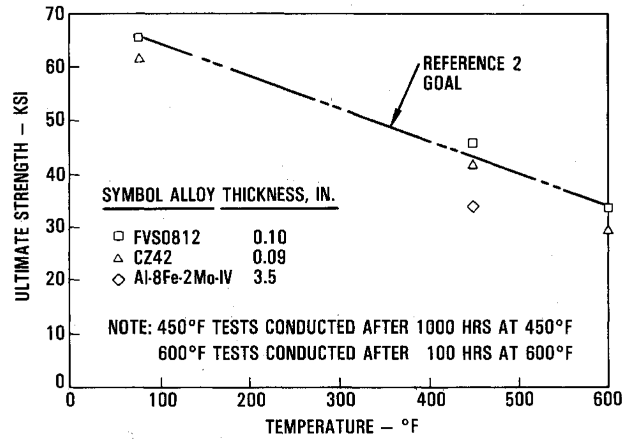

Fig. 5 Ultimate strength vs temperature for candidate elevated temperature aluminum extrusions.

ness goals. Acceptable toughness was displayed by the CU78 alloy, although strength levels were approximately 8 ksi lower than the FVS0812 alloy.

The average elevated temperature tension properties are compared with the development goals in Fig. 5. Typical CZ42 and FVS0812 properties are approximately equal to the ultimate design property goals, with the FVS0812 alloy demonstrating slightly higher strength at room temperature and 600°F. The strength advantage of the FVS0812 alloy is more significant at elevated temperatures. At 600°F, the FVS0812 alloy exhibited a 6 ksi improvement in yield strength over the CZ42 alloy. The elastic modulus of the FVS0812 alloy was also considerably higher at 600°F. None of the alloys evaluated showed any significant decrease in room temperature strength after exposures of 1000 h at 450°F and 100 h at 600°F.

The best combination of fracture toughness and room and elevated temperature tension properties were demonstrated for the FVS0812 extrusion alloy. The FVS0812 alloy was close to meeting the strength goals and exceeded the elastic modulus goals while maintaining acceptable fracture toughness. Material design properties for this extrusion alloy are being developed to provide a basis for current trade studies. A second alloy was not selected for extrusions because a scale-up in billet size is not required for the extrustion sizes generally required in fighter aircraft structure.

Forged Products

The average longitudinal room temperature tension properties for the CZ42, FVS0812, and Al-8Fe-2Mo alloy forgings are shown in Fig. 6. Properties for the CZ42 forgings that received the toughness improvement processing were obtained in the program cited in Ref. 2. Al-8Fe-2Mo forging data were based on flat, hand forgings, whereas properties for the other alloys were for closed die shapes. In general, die forging strength properties are slightly lower than hand forgings.

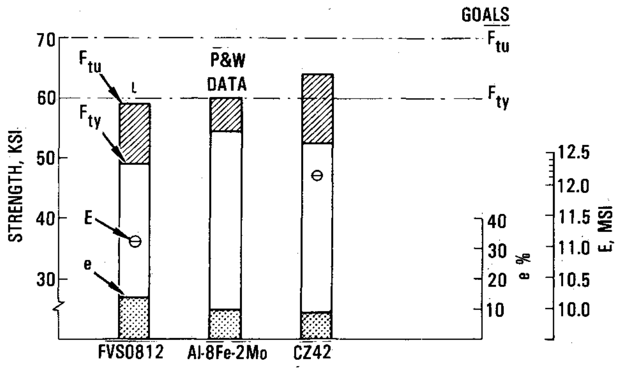

Fig. 6 Typical room temperature tension properties of elevated temperature aluminum forgings.

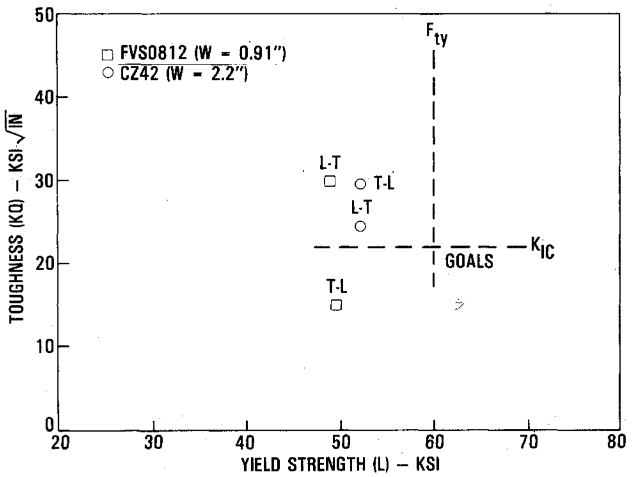

Fig. 7 Fracture toughness vs longitudinal yield strength for candidate elevated temperature aluminum forgings.

The CZ42 alloy demonstrated the highest strength of the forgings, with a typical ultimate strength of 64 ksi and yield strength of 53 ksi. The ductility of this alloy was 9–12%. The Al-Fe-Mo data indicated a slightly lower ultimate strength with comparable yield strength and ductility values. The FVS0812 alloy was somewhat lower in strength than the Al-Fe-Mo and Al-Fe-Ce forgings, with improved ductility.

Results of the plane strain fracture toughness tests are shown in Fig. 7. The CZ42 forgings exhibited a slightly better combination of room temperature strength and fracture toughness than the FVS0812 alloy. The transverse-longitudinal (T-L) toughness properties of the FVS0812 forging were lower than conventional high-strength aluminum forged parts. No data were available for the Al-Fe-Mo forgings.

Material Design Allowables

The recommended elevated temperature aluminum alloy materials for the aft fuselage center keel beam structure of an advanced tactical fighter include CZ42 and FVS0812 sheet and plate, FVS0812 extrusions, and CZ42 forgings. Selective reinforcement of the beam caps with MMC 6061 Al/SiC_f hot molded sheet was considered as a design option to improve structural weight savings. A set of material design allowables were determined from available property data, and are discussed in detail in the following sections on structural concepts and trade studies.

Design Trade Studies

Baseline Titanium Structure

A center keel beam in the aft fuselage between the engines of a generic advanced tactical fighter, shown in Fig. 8, is the structure evaluated in the design trade studies. The baseline titanium design uses conventional built-up construction as shown in Fig. 9. The center keel beam consists of two full-depth z-stiffened sheet webs located 3.0 in. on either side of the aircraft centerline. The webs are designed to carry shear and pressure loading, in addition to distributing engine thrust loads. The beam webs are stabilized by vertical full-depth built-up frames at approximately 15.0-in. spacing. Close-out frames provide continuity for the main fuselage frames. The two butt line (BL) 3.0 beams are connected at the upper and lower surfaces by stiffened sheet fuselage covers.

A NASTRAN finite element model of the aft fuselage structure, developed in support of the program cited in Ref. 4, was used to provide the internal loads necessary for detail design of the center keel beam. External loads applied to the model were enveloping net loads that account for nonstructural masses, as well as dynamic and aeroelastic effects. The thermal environment was accounted for in the finite element model by applied thermal gradients and elevated temperature material properties. Critical internal loads were extracted from the finite element model analysis results. Design details were established using internal loads at three critical locations. These loads represent critical net flight loads, engine conditions, and thermal gradients. Pressure loads were superimposed to obtain maximum design loads.

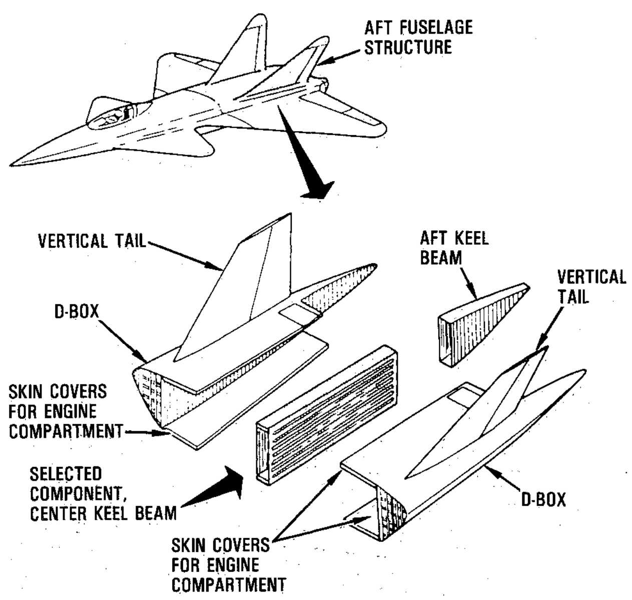

Fig. 8 Component selected for design trade studies.

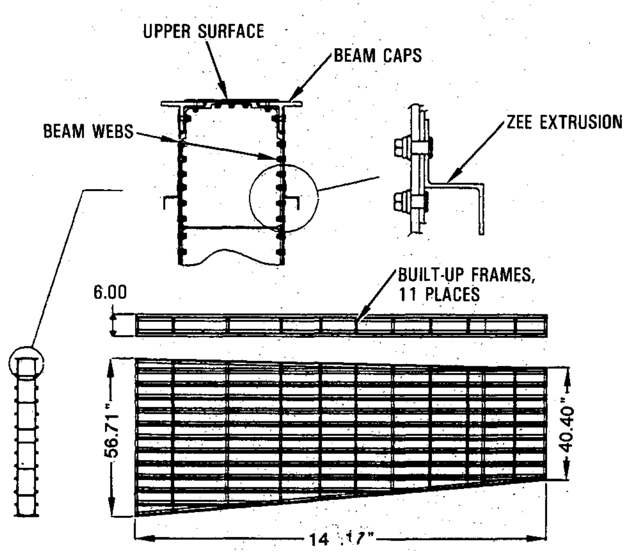

Fig. 9 Center keel beam (baseline titanium structural configuration).

Weight and cost analyses were conducted for the baseline conventional titanium keel beam design. Results of these analyses are presented in Tables 2 and 3. The cost analysis was performed to establish recurring acquisition cost for the baseline comparison system. The following assumptions were maintained for all acquisition cost calculations (learning curve assumptions based on C-130 cost production history): 1) all costs are in 1986 dollars, 2) total production is 300 aircraft at a rate of 60 per year, 3) no profit or cost of money is included, 4) 89% fabrication learning curve, 5) 83% assembly learning curve, and 6) 30% material scrappage.

Design Considerations

The design of the web structure was given primary consideration because this is the hottest part of the assembly and comprises about 67% of the total structural weight (see Table 2). The design requirements for beam web and caps are summarized in Table 4. A postbuckled beam web design was determined to be more efficient than a shear resistant web design and, therefore, the lighter design concept. Horizontal stiffeners are more efficient than vertical stiffeners for stabilizing the beam because of the large beam depth and relatively high-pressure loading.

Various structural concepts were considered for the web design, as shown in Fig. 10, and included conventional built up, bead stiffened, truss-core sandwich, sine wave, and unistructure. Based on the following considerations, the three concepts selected for evaluation were the conventional built-up, bead-stiffened, and unistructure.

Conventional built up. This concept provides a baseline for comparison in both titanium and elevated temperature aluminum alloys.

Bead stiffened. A formed beaded sheet is either metallurgically bonded, adhesively bonded, or mechanically fastened to a flat continuous web. The all titanium version of this concept was chosen as an alternate baseline to allow comparisons between both conventional built-up and superplasticity formed (SPF) titanium technology.

Sine wave. This concept was not evaluated in detail because it is not as efficient as the other concepts for pressure-loaded structure.

Table 2 Center keel beam weights

Item	No. per shipset	Weight per shipset, lb
Beam webs	2	161
Web stiffeners	22	71
Beam caps	4	41
Covers	1	22
Center frames	12	52
Center keel beam	1	347

Table 3 Center keel beam costs

Item	Material, $/shipset	Labor, $/shipset	Total recurring, $/shipset
Beam webs/stiffeners	15,808	9,364	25,172
Beam caps	4,774	5,394	10,168
Beam assembly	12,056	32,493	44,549
Covers	1,388	978	2,366
Center frames	6,084	28,102	34,186
Assembly	5,853	16,040	21,893
Center keel beam	45,963	92,371	138,334
Installation		11,021	11,021
Total	45,963	103,392	149,355

Table 4 Structural concepts trade study design requirements

Criteria	Web	Web stiffener	Cap
Geometry	$H = 55$ in. $L = 100$ in. $b = 15$ in. t set by q, P, & b/t	$H = 15 \times t$ $W = 1.5$ in. t set by EI, P, & b/t	$W = 2.2$ in. $H = 1.0$ in. t set by q, N, P, & F_{br}
Ult. static loading	$q = 1500$ lb/in.	$P = 7.5$ psi	$F = \pm 2000$ lb
Thermal exposure	130 h at 390°F 2 h at 500°F	130 h at 390°F 2 h at 500°F	150 h at 290°F 130 h at 365°F
Sonic fatigue	$b/t < 100$	$b/t < 100$	—
Local instability	—	$b/t < 15$	$b/t < 15$
General instability	—	EI set to force node in buckling wave form	—
Other	Post buckled <5 – isotropic <3 – orthotropic	Fasteners at $6D$ spacing	Fasteners at $4D$ spacing

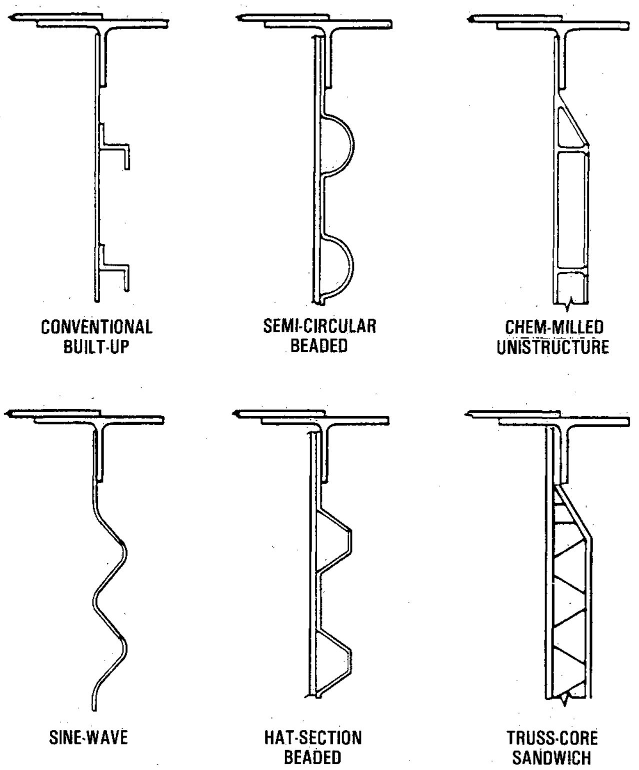

Fig. 10 Structural concept alternatives.

Truss-core sandwich. This concept is both heavier and more costly to fabricate than the other designs and, therefore, was not considered for further evaluation.

Unistructure. This concept is machined and chemically milled from a plate product. This is a very efficient structural concept, although material scrappage is relatively high.

The materials considered in this trade study include Ti-6Al-4V (baseline), elevated temperature aluminum, metal matrix composite (MMC) 6061 Al/SiC_f, graphite/polyimide composite. The design properties used for the analysis are given in Tables 5 and 6.

Structural Design

The structural sizing addressed sonic fatigue and flange stability, both of which are based on aspect ratio, and ensured that minimum gauge conditions were not violated. Stress analysis of the components was performed based on the design, material properties, and loading to ensure that the design strength and stability requirements were met. The stability critical structures were the beam and frame webs, web stiffeners, and the upper skin. The strength critical structures included the beam caps, frame flanges, and lower skin.

The keel beam web was designed to react a combination of applied shear and pressure, as well as engine thrust loads. The web was required to be shear resistant to 110% of design limit load, and the critical elastic shear stress was calculated using classical bucking equations for simply supported thin shells. Ultimate diagonal tension stresses were evaluated for the orthotropic materials but were not significant due to the shear resistant web design. The internal pressure in the engine bay induced both bending and membrane stresses in the unsupported web. A conservative clamped-edge condition was assumed, and the maximum combined tensile stresses were determined using large deflection theory. The stresses for isotropic materials were simply checked against the material tensile allowables. In the case of the orthotropic materials, the boundary reactions were determined and input along with the shear flow into a laminated plate program used to determine ply level strains due to combined loading of the laminate. For the MMC Al/SiC_f, room temperature properties were used for this analysis. Empirical reduction factors were then used to account for thermal degradation. In the case of the graphite/polyimide composite, insufficient empirical data existed, so estimates of thermally degraded properties were used for the analysis, with cutoff strains established for graphite/epoxy composites.

Horizontal web stiffeners stabilized the web and acted as panel breakers. Stiffener spacing ranged from 3.5 to 9.0 in. The web stiffener had to be stiff enough to force nodal web buckling and be able to react the bending stresses developed by the pressure acting on the web. General instability (GI) was the primary design driver for the stiffeners. The stiffness of the web/stiffener assembly was calculated and compared to a graphically derived minimum value required to prevent general instability for a given panel aspect ratio with simply supported edges. The web and stiffener parameters, specifically thickness, height, and flange width, were adjusted to prevent general instability as a failure mode. Once the GI requirements were satisfied, a strength check was performed to ensure that the beam was capable of reacting the pressure-induced bending stresses.

Full-depth internal frames were used to react engine bay pressure and flight loads and to provide load path continuity for the aft fuselage frames. Vertical flanges reacted the tensile loads due to pressurization of the engine bay, and horizontal ribs reacted compressive loads and stabilized the shear webs. A general instability analysis similar to that employed for the keel beam web/stiffener combination was used to analyze the frame web and ribs.

Critical flight conditions for the upper skin induced axial compression and shear loading. Upper skin stability was evaluated by calculating the buckling ratios for a simply supported shell for uniaxial compression and shear loading An empirically derived interaction equation was then used to determine the critical buckling stresses for the combined loading condition. Because of the biaxial loading of the skins, a Von Mises

Table 5 Isotropic material properties

Material	Density, lb/in.^{3}	Ultimate tensile strength, ksi	Tensile yield strength, ksi	Compressive yield strength, ksi	Ultimate shear strength, ksi	Tensile modulus, msi
Elevated temperature (Al-Fe-Ce or Al-Fe-V-Si)	0.106	39.0	34.0	34.0	22.5	9.0
Titanium[a] (6 Al-4V)	0.106	100.0	83.0	86.9	57.7	13.4

[a]Properties at 500°F, after 100 h exposure at 500°F.

Table 6 Orthotropic material properties

Material	Density lb/in.	Moduli of elasticity, msi E_L	Moduli of elasticity, msi E_T	Shear modulus, msi G_{LT}	Poisson's ratio ν_{LT}	Strain to failure, in./in. Tension E_L	Tension E_T	Compression E_L	Compression E_T	Shear γ_{LT}
6061 Al/ SiC_f[a] (50% 0°, 50% ±45°)	0.102	27.0	6.0	2.4	0.29	0.0093	0.0025	0.0093	0.0025	0.0100
Graphite/ polyimide[b] (50% 0° 50% ±45°)	0.057	19.0	1.2	0.7	0.30	0.0040	0.0045	0.0090	0.0200	0.0345

[a]RT properties from laminate analysis—reduced for temperature. [b]390°F after exposure to 500°F.

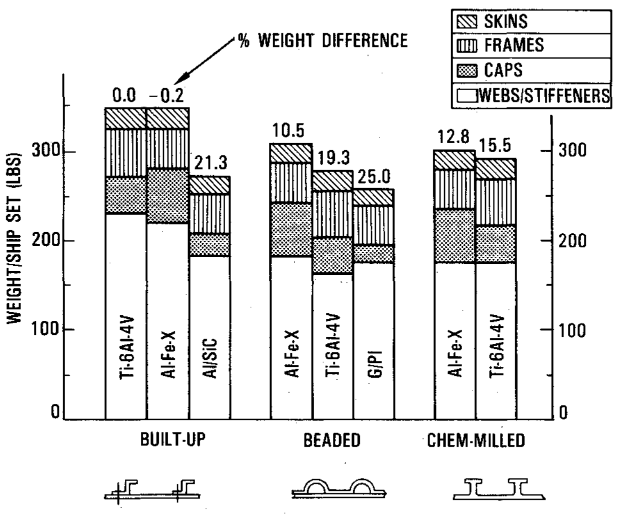

Fig. 11 Weight comparison for different design concepts.

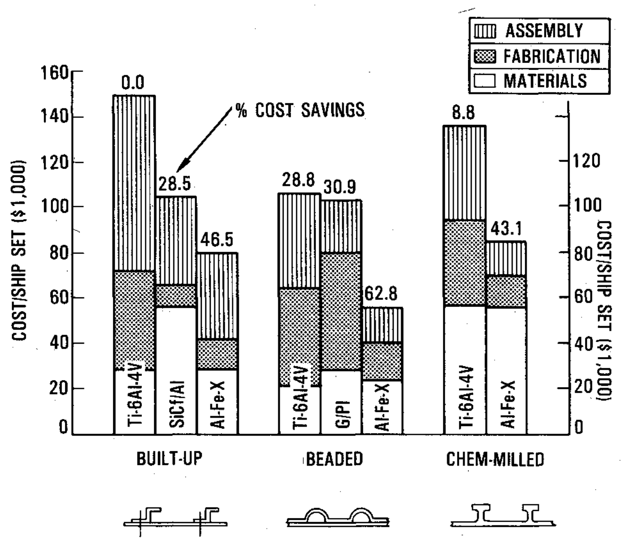

Fig. 12 Total recurring cost savings comparisons for various design concepts.

equivalent stress was used to determine the margins of safety. The lower skin was analyzed for net-section tensile strength.

Weight and Cost Comparisons

Results of the weight analysis are presented in Fig. 11. The breakdown by structural component gives visibility to the contributions of the various elements to the center keel beam total weights. As shown, the graphite/polyimide composite beaded web design concept yields the lowest center keel beam total weight with a weight savings of 25% compared to the baseline titanium design. Relating the Al-Fe-X design concepts to the baseline comparison system, the beaded web concept is 10.5% lighter and the chem-milled concept is 12.8% lighter than the titanium baseline. An additional weight analysis was conducted to determine the effect of reducing the operating temperature. The analysis demonstrated that a reduction in thermal exposure of the structure to 400°F would result in weight savings of 30.7 and 32.4% for the bonded/beaded and chem-milled web concepts, respectively The lower thermal exposure of the structure could be achieved by applying a thermal blanket to the beam webs. The thermal blanket would also prevent damage to the structure in the event of an engine fire. No calculations were conducted to estimate the additional weight required for the thermal protection system.

The cost analysis examined relationships between physical and performance characteristics and cost for previously produced advanced material structures. Primary attention was directed toward part fabrication man hours and material costs because these elements represent the largest contributions to cost for advanced material structures. Material cost and labor cost factors for advanced materials used in the cost analysis and results of the cost analysis are presented in Fig. 12. The Al-Fe-X beaded web concept is the lowest cost design concept with a cost savings of 62.8% over the built-up titanium baseline design. The built-up and chem-milled web concepts em-

Table 7 Hybrid design weight and cost analysis

Component	Structural concept	Material	Weight, lb	Acquisition cost, $
Beam webs	Bonded/beaded	Al-Fe-X	183.8	15,795
Beam caps	Hot-molded laminate	Al/SiC$_f$	24.8	5,646
Internal frames	Forgings and sheet/extru.	Al-Fe-X	44.0	13,486
Upper and lower covers	Sheet	Al-Fe-X	21.6	2,223
Assembly and installation				15,288
Center keel beam			274.2 (20.9% savings)	52,438 (64.9% savings)

ploying elevated temperature aluminum alloys provided 46.5 and 43.1% cost savings, respectively, over the titanium baseline.

A final weight and cost analysis was conducted to maximize weight and cost savings for a hybrid center keel beam design compared to the baseline design. The hybrid design incorporates structural concepts and advanced materials on a component basis that maximizes potential savings. The results of this analysis are shown in Table 7. This hybrid design provides a weight savings of 20.7% and an acquisition cost savings of 64.9% compared to the titanium baseline design for an operating temperature of 500°F.

Conclusions

The material properties of elevated temperature aluminum alloys show potential for aircraft structural applications in the temperature range of 300–600°F. Alloys demonstrating the best combination of properties are Al-7.1Fe-6.1Ce (CZ42) and Al-8Fe-1V-2Si (FVS0812). These alloys have been evaluated in sheet, plate, extrusions, and forgings from billet sizes of 110–750 lb. Based on design trade studies, weight savings of 12.8% and cost savings of 46.5% can be achieved using elevated temperature aluminum alloys in lieu of titanium for a center keel beam structure in the aft fuselage of an advanced tactical fighter. A hybrid design incorporating MMC Al/SiC$_f$ beam caps provides savings in weight of 20.7% and in acquisition costs of 64.9%.

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