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SYNTHESIS, PROCESSING, AND MODELLING OF ADVANCED MATERIALS

- Second ASM Paris Conference -

Editors: F.H. Froes and T. Khan

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Synthesis, Processing, and Modelling of Advanced Materials

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Synthesis, Processing, and Modelling of Advanced Materials

SECOND ASM PARIS CONFERENCE : SYNTHESIS, PROCESSING, AND MODELLING OF ADVANCED MATERIALS

FOREWORD

The second ASM Paris Conference on advanced materials, with emphasis on synthesis, processing, and modelling of materials was held in Paris, France, September 11-13, 1991. The theme of the meeting was selected to recognize that materials have matured to the stage where significant advances in the future require more than the traditional microstructure-mechanical property relationships approach. Rather much greater emphasis must be placed on synthesis/processing and modelling of advanced materials to achieve enhanced levels of physical and mechanical performance.

The conference attracted 140 delegates from 15 countries representing both research and industry. This was the first successful attempt to bring together North American and European experts through ASM International in Europe. The oral presentations gave a good overview of the latest state of research and technology in light metals, metal matrix composites, modelling, advanced processing and thermodynamics.

The editors of these proceedings were also the organizers of the conference. However, without the help of a number of other people, this conference would not have been possible. We would like to recognize the presenters of the various papers, and the chairmen of the sessions - Paul Costa and Ed Dulis (Overview of Aerospace Materials), Martin Wells and Don Neal (Light Metals - Aluminium and Titanium), Bert Westwood and Malcolm McLean (Steels, High Temperature Materials and Magnesium), Pierre Montmitonnet and Ed Nelson (Modelling), Georges Martin and Art Metcalfe (Advanced Processing and Thermodynamics) and Jack de Barbadillo (Powder Metallurgy and Metal Matrix Composites). Additionally the overall encouragement of Randy Cicen of ASM International was most helpful.

Finally, we express our thanks for co-sponsorship to the Société Française de Métallurgie et Matériaux.

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ADVANCED AEROSPACE METALS REQUIREMENTS AND CHARACTERISTICS - AN OVERVIEW

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ABSTRACT

The increased performance demands of emerging aerospace systems - both engines and airframes - require materials of construction which are "stronger, stiffer, hotter, lighter, and more cost-affordable". Developing systems will be discussed including the National Aerospace Plane (NASP) and the Integrated High Performance Turbine Engine Technology (IHPTET) programs. These systems will then be related to required materials characteristics. It will be pointed out that the advanced materials for aerospace application in the twenty-first century will require a total engineering approach involving not only the traditional chemistry-processing-structure-properties-applications relationship but also considerations such as life prediction, producibility, durability, reliability, inspectability, and maintainability. And one more "ility" which should never be forgotten - affordability (cost); in other words a total life cycle engineering approach. Key to the development of improved performance materials are innovative synthesis techniques which will allow novel microstructures and improved mechanical property combinations. Developments in eight areas of synthesis/processing-advanced metals will be reviewed in this paper: aluminum-lithium, spray deposition, nickel based superalloys, titanium aluminides, rapid solidification, mechanical alloying, electron beam vapor deposition, and thermochemical processing.

Conducted in part under the joint Moscow-Moscow Cooperative Program on the Synthesis and Processing of Advanced Materials.

INTRODUCTION

The three most important industries in driving technological change, national security considerations, and economic advances into the next century are information/communications systems (computers), biotechnology, and advanced materials and syntheses/processes[1-15]. Further, of these three, advanced materials and syntheses/processes are the most critical and considered vital to advancements in the other two fields, hence the major emphasis being given to advanced materials and the synthesis and processing of these materials in many parts of the world.

Advanced materials may be defined as materials which have enhanced mechanical and physical characteristics compared to traditional materials, such as aluminum and steel, currently manufactured in large-volume assembly line type facilities. The characteristics either allow for very significant improvements in product or device performance or, of even greater significance, allow for new technologies that are not achievable using conventional materials. The advanced synthesis and/or processing techniques are those methods used to produce these advanced materials.

The present paper will discuss developing aerospace systems and the metals required to meet performance demands; with the caveat that there are also non-metals (ceramics, polymers) being produced which also have considerably better performance than conventional materials of construction. While performance and synthesis/processing will be emphasized, another major concern with advanced materials will also be addressed-that of affordabilty (cost).

DEVELOPING AEROSPACE SYSTEMS

The systems of the twenty-first century will be more maneuverable, including very short take-off and landing (V/STOL) concepts to reduce dependence on large and fixed operating bases, and will also have increased speed capability. They will include aircraft with greatly increased range and reduced fuel consumption over current systems. Pay load will be increased while building-in varying degrees of stealth, instantly reactive knowledge-based defensive and offensive systems, and increased confidence (decreased inspection, increased reliability and decreased maintainability). Access to space in an affordable and predictable manner will be required, with greatly decreased turn-around times and much larger payloads.

Among the systems under various stages of development are supersonic V/STOL concepts, air superiority fighters featuring agility with thrust vectoring, high Mach number interceptors and bombers, advanced helicopters, including tilt-rotor concepts, light-weight fighters and high speed civil transports (Mach 2-5) which combine low noise and emission, with fuel efficiency (Figs. 1-4). There is likely to also be trend towards unmanned autonomous systems.

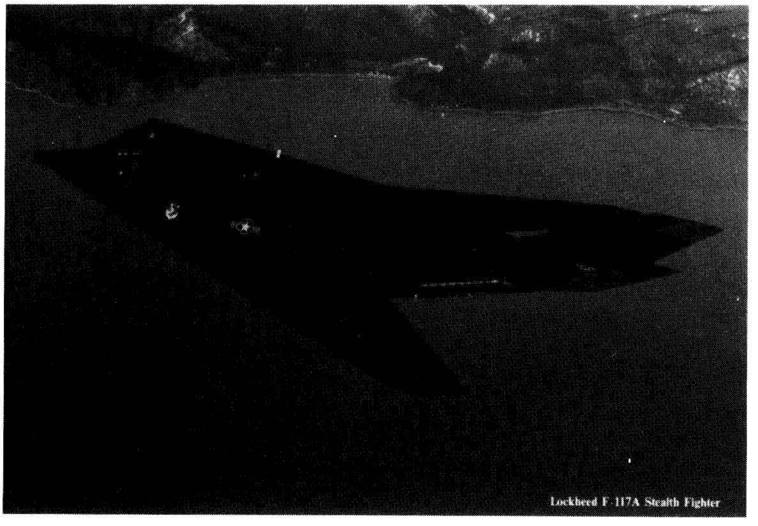

Fig. 1. F-117A Stealth Fighter (Courtesy Lockheed).

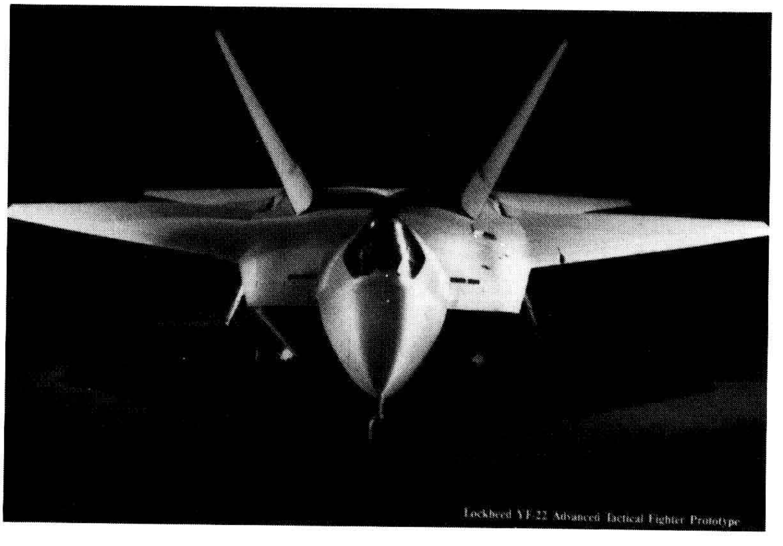

Fig. 2. YF-22 Advanced Tactical Fighter (Courtesy Lockheed).

Fig. 3. Artist's Conception of Boeing 777.

Fig. 4. Artist's Conception of the High Speed Civil Transport (HSCT).

In the space arena major emphasis is on development of single-stage to orbit hypersonic flight vehicles.[16] These include programs in the US, USSR, Britain, France, Germany, and Japan (Figs. 5-7). In the US the National Aerospace Plane (NASP) program has been in full swing for about 5 years with a first flight scheduled for the mid 1990's. This manned vehicle will require low density-high temperature materials for construction, with contending materials including monolithic or composite titanium aluminides, reinforced conventional titanium alloys, carbon/carbon composites, and other advanced metal matrix composite concepts.

Fig. 5. Artist's Rendition of One National Aerospace Plane (NASP) Concept (Courtesy Rockwell International).

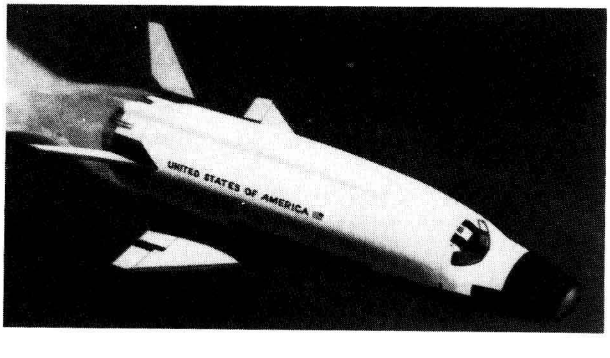

Fig. 6. Single-Stage-To-Orbit (SSTO) Concept that would Take-off Vertically from a Launch Pad and Land on a Runway (Courtesy Rockwell International).

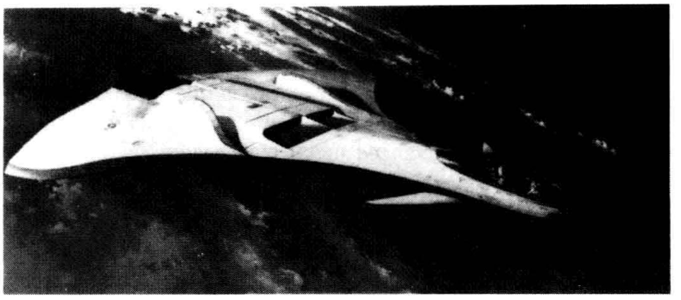

Fig. 7. Artist's Conception of United States Air Force Transatmospheric Vehicle of the Next Century.

The power units for the advanced systems will include low bypass turbofan engines at speeds up to Mach 2, and turbojet engines with afterburners to speeds above Mach 3 (Fig. 8). Hypersonic aircraft will require multiple-mode engines for conventional take-off, acceleration to hypersonic or transatmospheric cruise, and conventional landing. This could include take-off and landing with conventional turbine engines, acceleration to Mach 6-12 with a scramjet (supersonic combustion ramjet), and final attainment of orbital velocity with a rocket engine.[17] Even more advanced concepts include use of antiproton, directed energy, and nuclear propulsion systems.

In the USA the Integrated High Performance Turbine Engine Thrust (IHPTET) program is attempting to double the present thrust-to-weight ratio of the engine for fighter aircraft of the early next century, while decreasing fuel consumption by 50%.[18] Basically, this means hotter running engines, more highly loaded components, and a decreased part count. The material challenge involved is demonstrated by considering the limited capability of nickel-based superalloys to continue to meet increasing turbine inlet temperatures (TIT), particularly under conditions of reduced internal cooling air. Presently as much as 20% of the compressor delivery air is used for cooling turbine components, elimination of which could require a 500°C enhancement in material capabilities.[19]

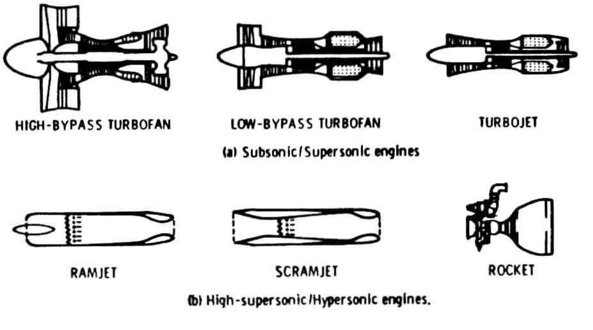

Fig. 8. Types of Aircraft Engines Used for Different Flight Envelopes (17).

ADVANCED AEROSPACE METALS

Structural metals with improved mechanical characteristics compared to present day metals will be necessary to enhance the performance characteristics of aerospace systems of the next century. These systems will require new materials which are "stronger, stiffer, hotter and lighter" than traditional materials of construction. Additionally, the materials may be "tailored" to have the properties required for a given application by use of composite concepts.

In using engineering structural materials, it is necessary to balance the so-called "unconstrained" characteristics against the "constraining" characteristics. It is necessary to move from the present day trend band to an enhanced trend band by innovative chemistries, processes, and microstructures (Fig. 9). To achieve these latter characteristics we can no longer stay with the "basic" materials of today and must instead move on to the "tailored" or "engineered" materials of tomorrow.

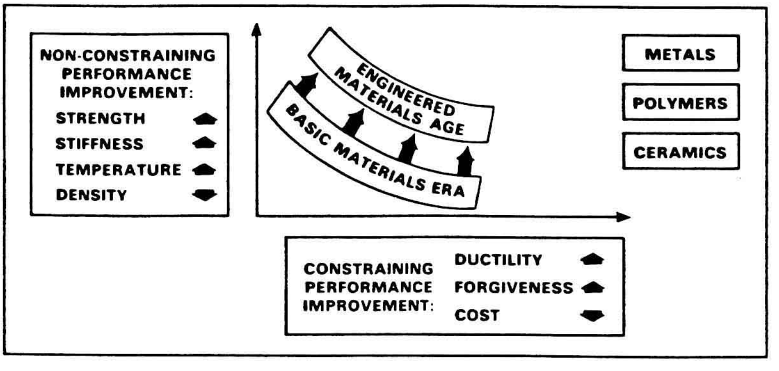

Fig. 9. Trend Bands of Conventional Materials of Today and Advanced "Engineered" or "Tailored" Materials of Tomorrow.

SYSTEM COSTS

The aerospace market is a "niche" market in which advanced structural materials tend to be technology driven, with the major emphasis on performance rather than cost, in contrast to other industries (Fig. 10), and cost strongly dictates sales volume (Fig. 11).[1] From the producer's perspective, volume sales require use in industries such as the automotive arena, but this will require low-cost fabrication techniques to be developed, contrasting with the low-volume aerospace industry.

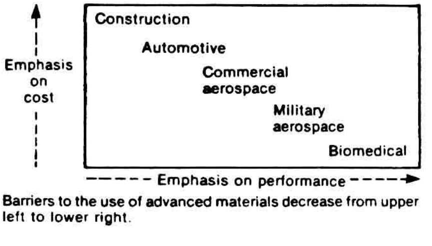

Fig. 10. Cost-Performance Emphasis in Various Industries.

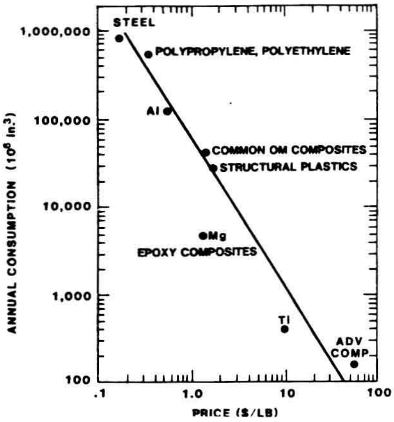

Fig. 11. Effect of Cost on Sales Volume of Various Materials.

Despite the emphasis on performance, cost of advanced aerospace systems will be a major concern, and only an integrated design, manufacturing, and use approach can lead to cost effective application compared to conventional materials use. These new materials must be considered as structures rather than in the same way as traditional materials such as metals, or initial acquisition costs could negate use, and prevent cost savings during operation due to the improved behavior.

Cost increase of fighter aircraft as the level of sophistication increases are shown in Fig. 12.[20] An aircraft such as the B2 which could cost as much as \$2.5B (with a 10 aircraft build) appears to fall on this same curve. One prediction is that at the present rate of increase of cost the U.S. Air Force will only be able to afford one new plane per year by the year 2050.

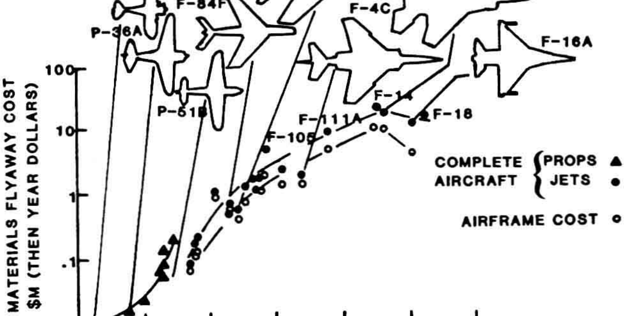

Fig. 12. Fighter Aircraft Flyaway Costs Versus Fiscal Year of Initial Operational Capability (Excluding Development) (20).

A further cost concern from the US point of view is the impact that increasingly expensive, high-technology aircraft coupled with restrictive US export control policies may have on the ability for the US to compete for foreign sales with European manufacturers in particular[21]. Even when the F-117A stealth fighter-bomber, the F-22 advanced tactical fighter and the planned AX follow-on to the A-6 become available for export, their high costs and sophisticated maintainability are likely to prove prohibitive to prospective overseas customers (Fig. 13). As just one example of price differential the F-22 will cost the USAF \$104M per copy (with a 648 aircraft buy) while the Light Combat Aircraft being developed in India will carry a \$15M price tag.

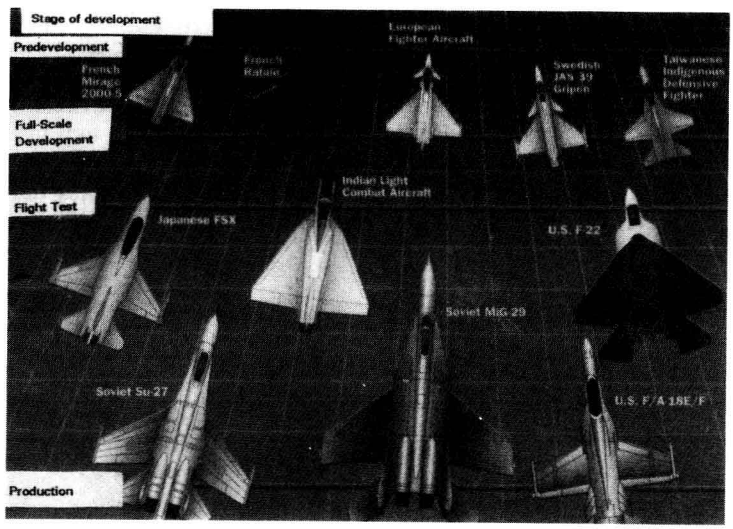

Fig. 13. Maturation of Various Advanced Military Aircraft (21).

ADVANCED METALS SYNTHESIS/PROCESSING

Synthesis may be defined as manipulation of a material at the atomic level to "build-in" desirable physical and mechanical characteristics. Processing may be considered as control of the material at a higher level, basically by manipuation of the microstructure. Processing also implies a change in the geometry of the material (shape) including near net shape processing.

There are many mature and developing synthesis/processing methods for advanced metals. Using the authors' prerogative we have chosen to highlight those presented in the following text.

ALUMINUM - LITHIUM ALLOY DEVELOPMENT

Aluminum alloys containing lithium as a primary alloying element offer many potential benefits including high strength, density reductions to over 10%, modulus increases to over 10%, excellent low temperature and cryogenic fracture properties, attractive resistance to crack initiation and fatigue crack growth (particularly for ΔK values exceeding 5 to 10 ksi $\sqrt{in}$), superplastic properties with excellent post-forming strength and excellent weldability.[22-24] In addition, Al-Li alloys, as a group (Table 1 and Fig. 14), offer reasonable resistance to corrosion, standard responses for formability, machinability, and chemical milling and good adaptability to surface finishes and coatings. Major concerns have been related to anisotropic properties, low combinations of strength and fracture toughness, and cost - the latter factor resulting from 1) the price of lithium, 2) low recovery (yield) from ingots, and 3) more stringent equipment and process requirements during casting and plant processing.

The development of Al-Li alloys started in the 1920's but despite serious alloy development programs in the US, and USSR during the 1950's and 1960's, these alloys found very limited acceptance in the aerospace community due to the concerns noted above. Prompted by continuing activities in the USSR, limited R & D efforts began again in Great Britain and the US in the early 1970's. Promising results from these activities resulted in a major resurgence of both fundamental studies and alloy development efforts in several Al-Li systems including, Al-Li-Mg, Al-Li-Cu, Al-Li-Mg-Cu, and Al-Li-Cu-Mg-Ag. Most of these alloy development thrusts included Zr as an important minor alloying element addition to control grain size/morphology.

	Alloy						
	2090	2091	8090	8090A	8091	X8092	X8192
Element[a]	Aloca August 6, 1984	C. Pechiney April 8, 1985	Alcan and C. Pechiney May 1985	Alcoa Late 1985	Alcan March 29, 1985	Alcoa May 1985	Alcoa August 1985
Si	0.10	0.20	0.20	0.10	0.30	0.10	0.10
Fe	0.12	0.30	0.30	0.15	0.50	0.15	0.15
Cu	2.4–3.0	1.8–2.5	1.0–1.6	1.1–1.6	1.8–2.2	0.5–0.8	0.4–0.7
Mn	0.05	0.10	0.10	0.05	0.10	0.05	0.05
Mg	0.25	1.1–1.9	0.6–1.3	0.8–1.4	0.5–1.2	0.9–1.4	0.9–1.4
Cr	0.05	0.10	0.10	0.05	0.10	0.05	0.05
Ni	—	—	—	—	—	—	—
Zn	0.10	0.25	0.25	0.10	0.25	0.10	0.10
Ti	0.15	0.10	0.10	0.15	0.10	0.15	0.15
Li	1.9–2.6	1.7–2.3	2.2–2.7	2.1–2.7	2.4–2.8	2.1–2.7	2.3–2.9
Zr	0.08–0.15	0.04–0.16	0.04–0.16	0.08–0.15	0.08–0.16	0.08–1.5	0.08–1.5
Other: each	0.05	0.05	0.05	0.05	0.05	0.05	0.05
total	0.15	0.15	0.15	0.15	0.15	0.15	0.15

[a] Numbers shown are either maximums or ranges.

Table I. The Chemical Composition of Aluminum-Lithium-Type Alloys Registered with the Aluminum Association as of March 1988.