Materials and Design 46 (2013) 552–560

Contents lists available at SciVerse ScienceDirect

Materials and Design

journal homepage: www.elsevier.com/locate/matdes

Review

Materials selection in design of structures and engines of supersonic aircrafts: A review

Zainul Huda [a,*], Prasetyo Edi [b]

[a] *Department of Mechanical Engineering, Majmaah University, P.O. Box 66, Majmaah 11952, Saudi Arabia*
[b] *Department of Aerospace Engineering, King Fahd University of Petroleum & Minerals, Dhahran 50603, Saudi Arabia*

ARTICLE INFO

Article history:
Received 16 June 2012
Accepted 1 October 2012
Available online 25 October 2012

Keywords:
Materials selection
Aerospace aluminum alloys
Superalloys
Composites
Configuration design
Supersonic aircrafts

ABSTRACT

This article reviews the advances in the materials selection for applications in structures and engines of current and future supersonic aircrafts. A brief overview of configuration design of the supersonic aircrafts is first given; which also includes techniques to improve configuration design for future supersonic aircrafts. The operating and ambient environmental conditions during supersonic flight and the resulting material requirements have been discussed; and consequently various aerospace aluminum alloys, titanium alloys, superalloys, and composites have been recommended. Finally, a new materials-selection chart is presented that would enable aerospace designers to select appropriate materials for application in high-performance current and future supersonic/*hypersonic* aircrafts.

1. Introduction

Supersonic aircrafts are capable of flying at speeds greater than 750 mi/h (1207 km/h) but less than 2000 mi/h (3219 km/h), and the Mach number $\mathbf{M}$ is greater than one, $\mathbf{1 < M < 4}$. The design of a supersonic aircraft and its materials selection must be based on sound engineering principles and practices since a small mistake in the design of the aircraft's fuselage, skeleton, wing, or any critical part could be fatal. The important material selection considerations in the design of a supersonic aircraft include: specific strength (strength-to-weight ratio), tensile mechanical properties, fatigue strength, low-speed impact strength, fracture toughness, notch sensitivity, fabricability, and resistances to crack propagation, stress corrosion, and exfoliation corrosion [1–3]. Another material requirement, directly related to the supersonic aircraft's design is the resistance to creep since long-term operation at Mach 3.5 may heat up the structure of the aircraft to a temperature around 300 °C [4,5].

One of the initial designs of the supersonic transport (SST) aircraft: *Concorde* was based on the selection of aluminum alloy as the basic structural material; this material selection was closely linked to the choice of Mach 2 as the design cruise speed. However, almost every country has rejected *Concorde* due to its sonic boom and possibility depletion of ozone due to the pollutants in the engine's exhaust. Sonic boom is the "thunder-like" noise produced when a plane is traveling faster than the speed of sound [6]. This is why; almost all the supersonic aircrafts designed to-date are military aircraft; which are mainly made of lightweight carbon-fiber reinforced polymer (CFRP) composite materials possessing high specific strength, fatigue strength, corrosion-resistance, and reasonably high creep strength [7,8]. Another practical requirement in the aerospace composites is their ability to be repaired when the skin of the aircraft panel becomes disbonded [9]. In addition to military aircrafts, CFRP are used in SCT aircrafts; for instance, much of the fuselage of the new Boeing 787 Dreamliner and Airbus A350 XWB are composed of CFRP. The physic of supersonic flow and its design are completely different from that of subsonic flow, about as great as the difference between civil and military aircraft. The unique features of supersonic aircraft design includes variable-swept/high-swept/delta-wing and thinner wing, canard, more slender fuselage, area ruling, sonic boom, more power-full propulsion system, variable engine air intake, and the like. Supersonic laminar flow also looks very interesting, especially for small aircraft. Although maintenance of laminar flow in a realistic operational environment has yet to be demonstrated, this concept remains very promising. A near term, environmentally acceptable supersonic business aircraft based on this technology with efficient subsonic overland flight appears quite feasible [10,11].

2. Current and future configuration designs

Prior to reviewing the progress in materials selection for supersonic aircrafts, a brief overview of the configuration design for

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* Corresponding author. Tel.: +966 554130411.
E-mail addresses: drzainulhuda@hotmail.com (Z. Huda), eprasetyo@kfupm.edu.sa (P. Edi).

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http://dx.doi.org/10.1016/j.matdes.2012.10.001

supersonic transport (SST) aircrafts is first presented. Typical SST aircraft configurations are presented in Fig. 1 [11].

The supersonic flight represents a domain in aircraft design with many challenges and with many remaining opportunities for conventional and unconventional solutions to long-standing problems. One of the most significant design parameters for future supersonic aircraft is the cruise Mach number. Mach numbers of 1.4–1.6 are lower than technically possible, but still provide large gains in speed relative to current civil aircraft, while appearing much more feasible in terms of efficiency and environmental impact. Small supersonic aircraft are especially attractive, with reduced community noise and more assured markets. The oblique wing/body configuration (Fig. 2a) appears promising for these lower cruise Mach numbers in terms of performance and boom, but still represents an engineering challenge, while the oblique flying wing offers the potential for very high efficiency, but likely results in a prohibitively large aircraft.

The Whitcomb area rule, also called the transonic area rule, is a design technique used to reduce an aircraft's drag at transonic and supersonic speeds, particularly between Mach 0.75 and 1.2. This is one of the most important operating speed ranges for commercial and military fixed-wing aircraft today, with transonic acceleration being considered an important performance metric for combat aircraft, necessarily dependent upon transonic drag. Typical wing planform use for supersonic aircraft is *double-delta wing* (Fig. 2b). The primary advantage of the delta wing is that, with a large enough angle of rearward sweep, the wing's leading edge will not contact the shock wave boundary formed at the nose of the fuselage as the speed of the aircraft approaches and exceeds transonic to supersonic speed [12].

Future high-speed supersonic aircrafts or the *hypersonic* aircrafts are being designed with ability to cruise at speeds >4.0 Mach [13,14]. The configuration design of the *hypersonic* aircrafts must take into consideration not only stresses but also the compressibility effects, ground ambient exposure and erosion effects due to weather conditions. As regards the compressibility effects, efforts are being made to design supersonic biplane with half-wedge wing resulting in reduced sonic boom and pressure drag [1]. Recently (2011), studies on erosion effects on the structure of supersonic aircraft have been made by Gohardani; who has suggested techniques to improve configuration design by altering geometrical parameters of the aircraft structure for avoiding erosion effects on advanced future supersonic aircrafts [15].

3. Operating conditions and materials selection for structure

3.1. Operating conditions

3.1.1. Environmental service conditions

An accurate understanding of expected service conditions is crucial in the selection of structural materials for the supersonic aircrafts. Additionally, the identification of design criteria, and the testing and evaluation of structural concepts are of paramount importance in the materials selection in designing current and future aircrafts. The variables that must be considered in designing both commercial and military high-speed aircraft applications include: operating stresses and temperatures, loads, ambient environmental conditions, moisture and fluid exposures, radiation, maintenance, and ground handling [16,17]. Exposure to extremes in temperature (ranging from about −30 °C to 370 °C), moisture (extreme humidity to desert conditions), and radiation (especially ultra-violet) can cause degradation of coatings and structural materials or exacerbate the damaging effects of flight exposure conditions. Discrete damage events, both on the ground and in flight, represent a threat to polymeric composite and thin-skinned components. Sources of discrete damage include hail impact, lightning strike, transport and handling, and foreign objects [18]. For supersonic aircraft, the flight-cycle conditions are determined by speed at cruise, altitude, flight loads, and spike (or failure) conditions. The SCT aircraft should be designed for a lifetime of approximately 20,000 flight cycles, which for a typical service cycle

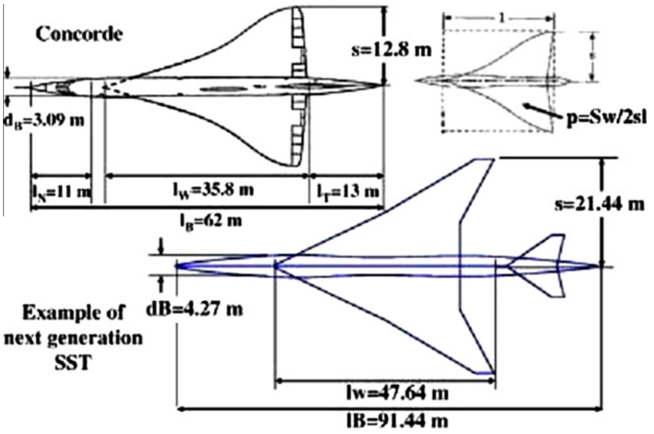

Fig. 1. Typical configurations for Concorde and next-generation supersonic transport (SST) aircrafts [11].

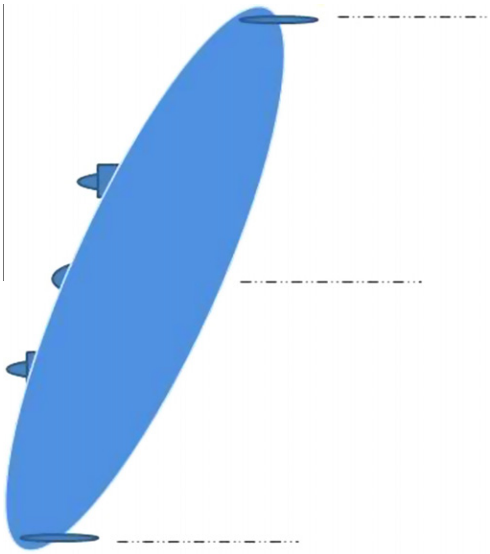

Fig. 2a. The oblique flying wing concept in supersonic aircraft.

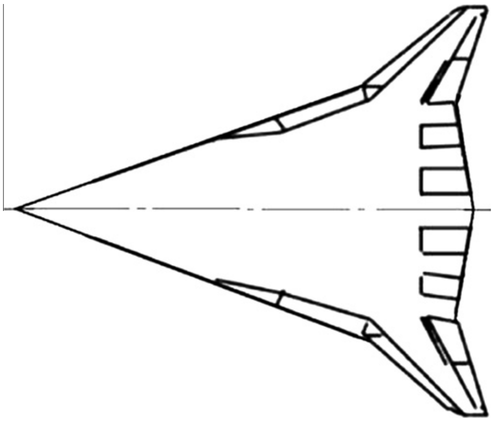

Fig. 2b. A typical double-delta wing planform in a supersonic aircraft.