CHAPTER 1

Properties and Characteristics of Aluminum and Aluminum Alloys

1.1 Melting of Aluminum and its Alloys

Unalloyed aluminum melts at a temperature of approximately 655 °C (1215 °F); it boils at approximately 2425 °C (4400 °F) (Ref 1.1, 1.2). Alloys of aluminum do not melt at a fixed temperature but rather over a range of temperatures dependent on their composition. For example, alloy 5456, with approximately 5% Mg alloying constituent, has a melting range of 570 to 640 °C (1055 to 1180 °F) (Ref 1.1, 1.2). Melting begins at the lower end of the range and is completed at the higher end. The melting ranges for many commonly used aluminum alloys are provided in Table 1.1.

Table 1.1 Melting ranges of some representative aluminum alloys

Alloy	Melting range		Alloy	Melting range	
	°C	°F		°C	°F
1100	640–655	1190–1215	5052	605–650	1125–1200
2024	500–635	935–1180	6061	580–650	1080–1205
3003	640–655	1190–1210	7075	475–635	890–1175

Source: Ref 1.1, 1.2

Aluminum and aluminum alloys are melted and remelted regularly as needed for the casting of ingots or billets for subsequent fabricating procedures such as rolling, extruding, drawing, or forging and also for recycling. Aluminum does not ignite or catch fire as it is being melted nor does it emit smoke or toxic gases.

1.2 Mechanical Properties of Aluminum Alloys at High Temperatures

The properties of aluminum alloys are compromised at elevated temperatures well before the metal reaches its melting temperature (Ref 1.3). For most of the alloys, strengths after significant times at temperatures above 150 to 200 °C (300 to 400 °F) are lower than those at room temperature, and the amount of the strength reduction may increase with both increasing temperature and/or increasing time at an elevated temperature. As a result, most aluminum alloys are not usually recommended for long-time service at or above these temperatures, but they are widely used in the temperature range from room temperature up to 150 to 200 °C. Certain alloys specifically designed to maximize high-temperature resistance, such as those in the 2*xxx* aluminum-copper series, are usually chosen for applications in the higher end of this range.

Tables illustrating the high-temperature tensile properties of representative commercial aluminum alloys are included in Appendix 1.

1.3 Physical Properties of Aluminum Alloys

Several of the physical properties of aluminum and its alloys provide some protection when the alloys are near a fire in an adjacent structure and also lessen their increase in temperature in the early stages of a more immediate fire. Those physical properties include (Ref 1.4–1.7):

- The specific heat capacity of aluminum alloys (816 to 1050 J/kg · K, or 0.195 to 0.258 Btu/lb · °F), which is approximately twice that of steel (377 to 502 J/kg · K, or 0.090 to 0.120 Btu/lb · °F) (Ref 1.7). This means that it takes twice as much heat energy to raise the temperature of aluminum one degree as compared to a similar mass of steel. So in any fire, aluminum members would be relatively slower to heat. This advantage is retained as temperature increases, because the specific heat of aluminum alloys increases with temperature to the melting point (Ref 1.4).
- The thermal conductivity of aluminum and its alloys, which is 88 to 251 W/m · K, or 51 to 164 Btu (h · ft · °F), and increases with increase in temperature (Ref 1.4). This is several times the value for steels (11 to 63 W/m· K, or 6 to 37 Btu [h · ft · °F]) (Ref 1.7). Thus, heat from a localized source will be distributed along an aluminum structure in a

much more efficient manner, enabling it to be radiated off and minimizing hot spots. Also, if the structure is sufficiently massive, the aluminum can act as a heat sink to slow the rate of increase of temperature in the early stages of a fire, increasing the period of serviceability. This might make the difference in prolonging structural endurance in a fire and allowing time to evacuate a burning structure.

- The reflectivity of aluminum, which is very high—80 to 90% of incident radiation, many times that of bare steel, and reportedly 17 to 19 times greater than the usual painted steel structures (Ref 1.7). It remains very high, even at high temperatures and even for old and oxidized surfaces. Thus for bare aluminum or aluminum alloys, this high reflectivity also contributes to a slower rise in temperature and longer serviceability than for most structural steels during the early stages of a fire. Reflectivity is decreased if the aluminum surfaces are painted or become coated with soot.
- The emissivity of aluminum alloys (0.02 to 0.10 ε for most structural aluminum alloys), which is lower than that of carbon steels (0.10 to 0.80 ε) and stainless steels (0.27 ε) (Ref 1.7). This also contributes to the ability of aluminum alloys to heat up more slowly than steels in the early stages of a fire, allowing more time for occupants to escape the fire. While emissivity varies greatly depending on surface quality and cleanliness, steel members may heat up approximately four times faster than comparable aluminum alloy members in a non-engulfing fire (Ref 1.8).

As noted, these physical properties are most important if the aluminum components of the structure are nearby or adjacent to the main fire in another structure, but they may also be helpful in the very early stages of a serious conflagration in the immediate structure. If the aluminum members become heavily coated with soot, the advantages offered by the physical properties of the original components are diminished or nonexistent.

The physical properties of several typical aluminum alloys and a widely used structural steel are illustrated in Table 1.2 (Ref 1.2, 1.7). More com-

Table 1.2 Physical properties of representative aluminum alloys and steel

Material	Melting range, °C	Boiling point, °C	Melting heat, kJ · kg^{-1}	Specific heat, J · kg^{-1} · K^{-1}	Thermal conductivity	Emissivity, ε	Coefficient of thermal expansion, 10^{-6} · K^{-1}, 20–100 °C
1050-O	645–658	2425	390	900	229	0.02–0.10	23.5
5083-O	574–638	2425	390	900	117	0.02–0.40	24.2
6005A-T5	605–655	2425	390	940	188	0.02–0.40	23.6
ASTM E24 steel	1400–1530	2860	250	420	54	0.10–0.80	13.5

plete tables of the physical properties of aluminum alloys are included in Appendix 2.

1.4 Resistance to Burning in Normal Atmospheric Conditions

As illustrated in the tests described subseqe ntly, solid bulk aluminum will not burn and has never been observed to burn in air. Similarly, molten aluminum has not been observed to burn in air. In neither situation does aluminum give off smoke or any hazardous fumes. The natural oxide coating on solid aluminum forms very rapidly and inhibits reaction of the underlying solid aluminum to air, thereby contributing to its high resistance to burning.

Like finely divided metallic powders of most metals, aluminum powder is very flammable and is hazardous to handle (Ref 1.8); it is used to make explosives. In a fire, this behavior is entirely different from that of solid or molten aluminum. Even thin foils of aluminum are impossible to get to burn rather than melt.

Aluminum has been thoroughly evaluated for structures where fire may be encountered and is given the highest rating for such applications by ASTM Standards (Ref 1.9–1.11), British Standard 476 (Ref 1.12–1.16), European Communities Directives on Construction Products (Ref 1.17), and various U.S. building codes (e.g., Ref 1.18).

1.4.1 ASTM Standards (Ref 1.9–1.11)

ASTM Standard E108 Fire tests to determine combustibility of aluminum structural components of aluminum roofs and dome structures were made for TEMCOR Co. by United States Testing Company in accordance with ASTM Standard E108, "Standard Methods of Fire Tests of Roof Coverings." This test method was comparable to the fire test standards of Los Angeles Building Code 5702.01 (Ref 1.18), Underwriters' Laboratories Standard UL 790 (Ref 1.19), and National Fire Protection Association Standard 256 (Ref 1.20). Measurements were made of dimensional stability, weight loss, and appearance changes of pieces of the space frame truss. Aluminum sample panels, 1.97 mm (0.055 in.) thick, were exposed to temperatures up to 825 °C (~1500 °F) for up to 10 min. There was some melting of the thin roof panels but no combustion, and, in fact, there were no dimensional changes of the space frame components observed. These tests and the results were described in two United States Testing Company Reports dated August 6 and 7, 1985 (Ref 1.21, 1.22).

ASTM Standard E136 A number of different aluminum alloys were tested by Signet Testing Laboratories in conformance with ASTM Standard E13- 65, "Combustibility of Materials in a Vertical Tube Furnace." The alloys were tested at 750 °C (180 °F) (Ref 1.5) for Kaiser Aluminum

& Chemical Company in the period from 1968 to 1972. Reports were issued by Signet dated September 30, 1968, covering alloys 3004 and 8112, and May 17, 1972, covering alloys 3003, 3105, and 5005 (Ref 1.23, 1.24). All alloys were rated "noncombustible."

Copies of representative reports documenting evaluations of the fire resistance of aluminum alloys and aluminum structures are contained in Appendix 3

1.4.2 British Standards (Ref 1.12–1.16)

Part 4 and now-obsolete Part 5 of BS 476 provided for tests for noncombustibility and ignitability, respectively, of structural materials (Ref 1.13, 1.14). Aluminum alloy test pieces, 40 mm (1.6 in.) in width and breadth and 50 mm (2 in.) in height, were exposed in a furnace to a stabilized temperature of 750 °C (1380 °F) for a period of more than 10 min. During this exposure, continuous observations were made on (a) whether the temperature in the furnace increased by 50 °C (122 °F) or more, which would indicate the material contributed to an increase in temperature, and (b) whether or not there was any period of flaming in the furnace for 10 s or more, which would indicate ignition. Aluminum alloys were not observed to ignite, flame, or contribute in any way to the temperature rise in the furnace. They were rated P for "not easily ignitable."

Aluminum was also tested in accordance with British Standard 476, Part 3, for flame spread and fire penetration of roof structures (Ref 1.12). In this test, aluminum alloy roofing structure samples at least 1.5 by 1.2 m in thickness were exposed to test flames of luminous coal gas or natural gas 200 to 250 mm long. External surfaces of aluminum demonstrated the highest resistance to both fire penetration and flame spread and were classified as AA. For inner surfaces, aluminum demonstrated very high resistance to flame spread and was classified as 0, the highest rating for that type of assembly (Ref 1.21, 1.23, 1.24).

Part 6 of BS 476 covers fire propagation performance for coated systems (Ref 1.15). Because of its hard oxide coating and excellent corrosion resistance with the need for only thin protective coatings, aluminum consistently achieves high ratings in this situation as well.

1.4.3 National Standard of Canada CAN4-S114-M80 (Ref 1.25)

In 1982, noncombustibility tests were run on aluminum alloy 6063 by the National Research Council of Canada in accordance with their National Standard of Canada CAN4-S114-M80. The tests were run in triplicate, with three specimens, 3.8 by 3.8 by 5.0 cm (1.5 by 1.5 by 2.0 in), held in a furnace stabilized to 750 °C (1380 °F) for a minimum of 15 min while being visually examined for flaming or smoking and subsequently weighed for weight loss. The conclusions from the tests were that aluminum "met the requirements for non-combustibility according to CAN4

S114-M80 since (a) maximum temperature rise was zero, (b) sample did not flame during the test, and (c) maximum weight loss did not exceed 20 percent.” The results were reported in NRC Report E-11-67, dated June 9, 1982, written by R.C. Monette and submitted by T. Harmathy (Ref 1.26).

1.4.4 Uniform Building Code (Ref 1.27)

Alloys 6061-T6 and 6063-T5 were tested in accordance with the requirements for incombustible materials of the Uniform Building Code published by the International Conference of Building Officials (Ref 1.27). In these tests, three pieces of structural extrusions of each alloy were subjected to temperatures of 650 to 655 °C (1205 to 1210 °F) for a period of 5 min with no observed ignition or flaming. They were all noted to conform to the requirements for an “incombustible” rating.

1.5 Burning in Pure Oxygen

Rapid oxidation of aluminum and other metals, including steel, has been reported in several laboratory investigations using a 100% oxygen environment (Ref 1.28–1.3). In these studies, solid aluminum was forced to oxidize rapidly when an oxygen-gas flame was trained directly on the aluminum specimen, melting the surface. Even then, rapid oxidation or burning occurred only after the oxide layer was mechanically removed. When the oxygen stream was removed, the reaction immediately stopped.

In a review article (Ref 1.28), the generalization was stated that “all metals, with the possible exception of gold and platinum, can be expected to ignite in oxygen at some elevated temperature.” Ignition-sensitive alloy systems were defined as alloys of titanium, zirconium, thorium, uranium, lead, tin, and magnesium. The article goes on to say that alloy systems rated to be relatively insensitive to ignition in an oxygen environment include austenitic stainless steels, nickel alloys, cobalt alloys, copper alloys, and silver alloys. A third group of alloys was described as intermediate between the sensitive and insensitive groups; that group includes aluminum alloys, carbon steels, low-alloy high-strength steels, and 400-series stainless steels.

It is clear that a 100% oxygen environment is required to get any rapid oxidation or ignition of aluminum and aluminum alloys as well as steels, and that any combustion stops immediately if the supply of pure oxygen is stopped.

1.6 Resistance to and Protection from Thermic Sparking

Accidents in the mining industry during the 1950s were attributed to the thermic reaction of aluminum striking or being struck by rusty steel. Uppal

(Ref 1.4) indicates that perhaps the greatest fear of offshore engineers in using aluminum components is the possibility of an explosion resulting from an exothermic reaction between rusty steel and aluminum creating a spark when the piece of aluminum strikes a steel component; this is referred to as thermite sparking.

Though relatively rare, these events spurred on a great deal of research by the aluminum industry, and the nature and methods for protection against such thermic reactions are now well understood (Ref 1.4–1.6).

Thermic sparking occurs when a blow of aluminum against rusty iron or steel results in a transfer of oxygen between intimately mixed aluminum and rust (iron oxide) particles. Explosions may result if the thermic sparking occurs in the presence of an ignitable environment.

However, it is important to note that thermic sparking requires a very specific set of pre-conditions to exist simultaneously at the time of contact, and these conditions are rarely met. Thermic sparking does not occur when aluminum is struck in a normal ambient atmosphere by other aluminum, nor with any other material, including non-rusty iron and steel. So overall, the likelihood of thermic sparking even under hazardous conditions is considered low, and it is essentially nonexistent under normal atmospheric conditions.

In those situations where there is some concern that aluminum might be directly in contact with rusty iron or steel in the presence of an ignitable environment of any kind, it is recommended that the aluminum surfaces be painted and the paint maintained in good condition.

Despite the original mining accidents that prompted so much study of thermic reactions, aluminum is now widely used and recommended for mining applications and has been for many years. For more detail on such applications and on the low risk of reactions in mining situations, the reader is referred to Ref 1.5.

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