Aerial White Paper

Thermal Characteristics of
Emergency One Extruded Aluminum Aerials

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Thermal Characteristics of Aluminum

The suitability of a structural material for fire fighting aerial apparatus should be based on all the applicable physical and thermal characteristics of that material. When the strength of aluminum at elevated temperatures is the only thermal property considered, it would seem to indicate its unsuitability for use as a structural material for fire fighting aerials. Further investigation however, shows it is in fact a very suitable structural material, as suitable as steel in normal high heat fire ground environments.

Comparisons between the suitability of aluminum versus steel for the structural members of a fire-rescue aerial device need to consider all of the material thermal characteristics - not just strength at a given temperature. Thermal conductivity, reflectivity, absorptivity and specific heat must also be taken into consideration. It is well known that aluminum has lower strength than steel at elevated metal temperatures. It is not as well known that it takes a much higher rate of heat input into aluminum to raise its temperature equally with an equivalent piece of steel. A brief discussion of the thermal conductivity, reflectivity, absorptivity, and heat capacity of aluminum and steel follows.

Thermal Conductivity

When a temperature gradient exists in a structure there is an energy transfer from the high temperature region to the low temperature region. This energy transfer is accomplished by conduction which is defined as the transfer of heat from one part of a body to another part by short range interaction of molecules and/or electrons.(1) The heat-transfer rate is directly proportional to the cross sectional area, the temperature gradient, and the thermal conductivity of the material. The defining equation for thermal conductivity is:

q = -kA(Tlow - Thigh)/(x2 - x1) (1-1) (2)

where q is the heat transfer rate measured in Watts (W), k is the thermal conductivity of the material with units of W/m . oC, A is the cross sectional area in m2, and T is the material temperature (oC) at location x (m).

The 6000 series of aluminum alloys has a thermal conductivity of 177 W/m . oC, approximately 3.3 times greater than medium carbon steel used in modern steel aerials which has a thermal conductivity of 54 W/m . oC(3). In addition, the thermal conductivity of aluminum increases as its temperature increases but steel thermal conductivity decreases as its temperature increases.

As shown in equation (1-1) the rate of heat transfer is directly proportional to the cross-sectional area of material available to move the heat. The wall thicknesses of E-One aluminum structural extrusions are from 2 to 3 times thicker than a comparably rated steel aerial. This greater cross-sectional area, when added to the significantly higher thermal conductivity of aluminum, results in heat being conducted away from the hot regions 6.6 to 9.9 times faster for an E-One aluminum ladder than for a comparable steel ladder.

Reflectivity and Absorptivity

Reflectivity is the fraction of incident radiant energy that is reflected away from the surface of a material.(4) Absorptivity is the fraction of incident radiant energy absorbed by a material and transformed into heat.(5) The swirled finish of an E-One aluminum ladders reflects most (93 to 95%) of the incident radiant energy that strikes it, absorbing only 5 to 7%.(6) White enamel paint similar to paint commonly used on steel ladders, only reflects about 9 to 13% of incident radiant energy, which means it absorbs from 87 to 91% of the radiant energy that strikes its surface.(7) This much higher absorption of the incident radiant energy for steel ladders painted white will cause their temperature to rise faster and higher than an unpainted aluminum ladder exposed to the same radiant heat environment.

Heat Capacity (Specific Heat)

Heat capacity is a measure of how much heat a mass absorbs before its temperature changes.(7) Aluminum has a heat capacity of 892 Joules/kg . oC while medium carbon steel has a heat capacity of only 465 Joules/kg . oC.(8) In other words, it takes almost twice as much heat input to raise one kilogram of aluminum 1 degree as it takes to raise one kilogram of steel 1 degree. Even though an E-One aerial has 2 to 3 times the metal cross-sectional area as a comparable steel ladder, it only weighs approximately 2/3 that of a comparable steel ladder. This means an E-One aluminum ladder has 1.9 x 2/3 or about 1.27 times as much heat capacity as a comparable steel ladder. Put another way, the aluminum ladder absorbs 1.27 times more heat than a comparable steel ladder for every 1 degree change in metal temperature.

Effects of Reheating

When precipitation hardened 6061 aluminum is welded the heat affected area right around the weld is converted back into essentially a solution heat treated state. Emergency One bases its 2.5:1 safety factor on the as-welded yield strength of 6061-T6 aluminum, which is 20,000 psi. Based on this yield strength, the maximum allowable primary stress at maximum rated operational load in any structural aluminum within one inch of a weld is only 8000 psi.

Table 1 lists the effects of reheating on the strength of 6061-T6 aluminum extrusion.

Table 1. Reheating Times for 6061-T6 Aluminum Alloy Resulting in Maximum Strength Decrease of 5% (9)

Alloy and Temper	Reheat time at 300 oF	Reheat time at 325 oF	Reheat time at 350 oF	Reheat time at 375 oF	Reheat time at 400 oF
6061-T6	100-200 hours	50-100 hours	8-10 hours	1-2 hours	30 minutes

The times shown are for the core temperature of the metal, not the ambient air temperature. As we have shown in this discussion, it will take some time to bring an aerial ladder up to these kinds of metal temperatures. In addition, the maximum design primary stress is only 8,000 psi, so the yield strength of the aluminum would have to decrease to below this level before the ladder would begin to deform at full rated load. The minimum yield strength of fully annealed 6061 aluminum is 8,000 psi and the minimum ultimate tensile strength is 11,000 psi (10). In effect the strength of an Emergency One aluminum ladder can not decrease below the maximum allowable primary design stress providing a minimum possible safety factor of 1:1. Even with fully annealed 6061 aluminum in the high stress areas of the ladder, the structure is still capable of holding maximum rated operational loads without material separation.

The area of maximum vertical stress in all Emergency One aerial designs is in the extrusions at the base end in the overlap area between sections. This area is well removed from the tip area of the ladder. This protects it from exposure to the hottest ambient environments. It is this area that would need to be reheated to the temperatures shown in Table 1 before the structural integrity of the ladder would be seriously affected.

The temperature indicators located at the tip of all Emergency One aerials turn black after they are exposed to a hot environment of 300 oF or more. The Emergency One maintenance manual clearly explains the procedure to follow should any of the temperature indicators turn black. The test for determining whether the metal of the ladder has been affected by exposure to high heat is a simple hardness test. Any competent testing company can perform the hardness test, and if hardness levels fall below the range given in the maintenance manuals, additional testing can be done with factory involvement to determine the extent of the damage.

Summary

An E-One aluminum aerial as compared to an equivalent rated steel aerial conducts heat from hot spots to cooler areas 6.6 to 9.9 times faster, absorbs 92% to 94% less incident radiant energy, and increases it's metal temperature 21% less for every unit of heat energy absorbed. To the fire fighter, this means that if an E-One aluminum ladder and a comparable steel ladder were placed side by side and exposed to the same thermal environment, the hot region on the steel ladder would be raised to a higher temperature in less time than on the aluminum ladder. The high conductivity, high heat capacity, and low absorptivity protect the aluminum from the negative effects of exposure to normal, high heat fire ground environments.

In addition, Emergency One's high safety factor and low design stress protect the ladder structure from catastrophic failure even if the material is fully annealed. Of course, a ladder that has been exposed to an environment hot enough to anneal the material should be removed from service
immediately. This is not normally a problem as a truck that has seen this hot of a fire ground would have just about every rubber and plastic part on it reduce to a puddle and would be unserviceable anyway. The effects of heat on aluminum are very well documented with a direct relationship between material hardness and strength. Hardness measurements can be correlated directly with material strength.

Actual thermal conditions and the subsequent response of aerial ladders at fire grounds is a highly complex and constantly changing scenario that involves radiant energy along with convection and conductive heat transfer. Convection heat transfer has not been addressed because it is not a function of the ladder structural material but is a function of the geometry and orientation of the associated structure and the convection fluid flow. This brief discussion of the thermal characteristics of aluminum and steel has not attempted to model actual fire ground conditions but has dealt with the basic thermal properties of the structural materials and has applied those properties to fire fighting aerial apparatus structural materials.

References:

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