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METALS FOR SPACE FLIGHT

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Flight into space is such a colassal concentration of energy, the jewler's precision of operation, and the actions controlling the operating and functioning mechanisms. In addition to this, there is also the enormous problem of materials - the most durable, stable, and effective as converters of energy, and the lightest. In space materials, the problem is qualitative - the concentration of properties per unit of weight or weight efficiency plays a major role. The qualitative degrees are often called specific characteristics. Specific density, for example, has a correlation of the limit of density σ_B to the specific weight γ; i.e., $k = \sigma_B/\gamma$. But, specific heat capacity is an amount of heat expended in heating a unit of weight.

Clearly, the greater the weight efficiency of a material the easier, as a rule, and cheaper for space equipment and rocket systems to be launched into orbit.

The Effects of the Conditions of Space on Materials

In space, not only man but all materials are affected by unusual conditions. Here there are the actions of deep vacuum, space cold, intensive solar and cosmic radiation, and fast-flying meteoritic particles. During launching and landing, one must consider intense aerodynamic heating, loads, and vibration.

We shall see how the various space conditions influence metals and other materials.

Deep Vacuum

A deep vacuum, first of all, is low pressure. At an altitude of 320 km, the pressure is 10^{-6} mm Hg, and as a spaceship departs the earth's surface to an altitude of its radius and greater the pressure becomes 10^{-12} mm Hg. At temperatures of 100 to 200 deg C, this is below vapor tension of many process metals. For example, zinc and cadmium, which are usually used as anticorrosion covers in aviation construction, in conditions of space would quickly vaporize and so they are excluded from consideration here.

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The vapor tension of zonc at these temperatures is on an order of 10^{-6} to 10^{-7}, and for cadmium, 10^{-4} mm Hg. Even magnesium, from which the bodies of the first American satellites - the Vanguard and Discoverer- were made, could operate at such altitudes only for limited periods (its vapor tension is 10^{-9} mm Hg). For increasing the period of its operation and increasing the stability (resistance) to micrometeorites a complex cover was used.

Aluminum, beryllium, iron, nickel, cobalt, titanium, and even many alloys do not vaporize and can function in space for long periods. Some refractory metals - tantalum, molybdenum, and others hardly vaporize even under intense heating. But, refractory chromium, when heated above 1400 deg C, evaporates intensely.

The loss of lubricating properties of ordinary liquid lubricants and absorbing films is explained by the high vacuum. Viscous (heavy) lubricants with low tensions operate for limited periods if the vacuum is not too profound (on an order of 10^{-6} mm Hg). During long periods of operation in a vacuum, particles of contact substances (their ions, atoms, and molecules) begin to intensely interact as a result of which there is a sharp increase of the coefficient of friction and deterioration. The surfaces of related materials cling together at the contact points. It was established that in space the most effective solid lubricant with low vapor tensions were of the grafite type (molybdenum disulfide), and so on.

Space Cold

Temperatures on the shadow side of a spaceship may reach -250 deg C and even approach absolute zero (-273.2 deg C). In addition, many metals and polymer materials become extremely brittle. This is basically connected with the nature of the material and its purity. Iron, molybdenum, chromium, tungsten, beryllium cold shorts are already a little impure. Nickel, copper, and aluminum retain a high viscosity at a very low temperature, even with significant impurities in crystal lattices.

Most rezins and plastics also abruptly lose their viscosity in the cold of space. But here, fluoro-plastics and a series of glass plastics can operate at very low temperatures.

Solar and Cosmic Radiation

Solar and cosmic radiation are most intensly increased outside the earth's atmosphere.

Intense radiation causes materials to heat, atoms to ionize, a mixture in crystal structures, the formation of various kinds of defects in structure, and the vaporization and dispersion of the space equipment.

The ordinary level of radiation in space, obviously, does not constitute a major danger to the stability to the metal and inorganic heat-resistant materials; but, organic polymeric materials, semiconductors, and several glasses can change their properties and even lose their efficiency under the influence of radiation.

Meteoritic Particles

Meteoritic particles which can strike a spaceship are of various sizes. Most frequently the particles are dust (microns). They strike spacecraft at velocities on an order of 10 to 70 km/sec. Microexplosions result from such collisions. A crater on the surface penetrates the polished surface which eventually becomes coarse. The coarse surface of the metal radiates heat which is approximately twice as intense as when a polished surface is affected. Consequently, the thermal balance of the craft may be upset.

However, in our specifications, there is a cover having a high-degree of blackness which practically does not react to the shallow flaws in the surface and stabilizes the thermal balance. There are also other methods for maintaining stabilization.

As has been demonstrated by research, the danger of damage to the face by much harger particles is not great; nevertheless, it must be considered especially during the design of the condenser-radiators of the power units the area of which may be quite large. Therefore, they are made of laminated materials having a high-degree of stability.

Aerodynamic Heating

The aerodynamic heating of space equipment takes place during launch and landing and especially during earth reentry. Satellites in orbits with a 300-km apogee have kinetic energies on an order of 2300 joules/kilogram and the energy level of an interplanetary spaceship reentering the atmosphere is twice that. During reentry, a basic part of the kinetic energy of braking results in heat which is transfered to the spaceship; as a result, the surface may reach temperatures of 1500 to 6000 deg C. The problem of eliminating the heat to prevent damage to the ship is solved with the aid of special reflective shields and heat absorbers (ablatives).

Construction Materials of High Specific Density; Alloys Based on Light Metals.

Materials used on spacecraft must be light and be characterized by a high-specific density. Obviously, we must find these from the very lightest chemical elements, as shown in the upper left-hand corner of Mendeleev's table in Fig. 1.

One of the lightest metals used in space is aluminum ($\gamma = 2.7$ g/cm^3, the melting point is (t_{melt}) = 660 deg C). In its pure form, this material has low stability ($\sigma_B = 4$ kg/mm^2); but, with other elements and after appropriate heat treatment, we have a material with a stability on the order of 40 - 70 kg/mm^2 and a specific density of K = 15 to 25. It was from one such alloy that the shell of the first AES was made and launched into orbit on 4 Oct. 1957.

The most prevalent (material) is Duralumin. It can withstand temperatures of 100 to 120 deg for long periods of time. As a result, oxides on its surface produce a solid coating, usually of aluminum oxide Al_2O_3 which is characterized by high hardness and a melting point (≈2050 deg C). This increases the stability of the construction to the action of micrometeorites.

An even more efficient special heat-resistant alluminum alloy are those such as SAP (САП) (baked aluminum powder) or SAS (CAC) (baked aluminum alloy). They are used to temperatures of 300 to 500 deg C. At 250 to 350 deg C, when the stability of most aluminum alloys is usually sharply lowered, with these it is retained to levels of K = 10 to 15. The stability of these alloys may be further increased by adding to the composition . fine sappharine fibres. Such materials are sufficiently effective and cheaper than titanium alloys.

MAGNESIUM. Magnesium has a similar melting point and is one-third lighter than aluminum. The specific density of its alloys are like those of aluminum. If it were not for the requirement for high-stability, the parts made of magnesium could be preferable considering how much lighter it is.

Magnesium is more brittle than aluminum but is better formed by cutting. Although its modulus of elasticity is less than that of aluminum, its hardness per unit weight is considered extremely great if one considers its much lower specific gravity.

Complex alloying made it possible to obtain an alloy characterized by a high specific density at sufficiently wide intervals of operating temperatures and with good characteristics.

TITANIUM. This was introduced to everyday use 20 years ago. Being more than 40% heavier than aluminum, it has 3 - 6 times greater density and more than 2 times the absolute melting point. In acid, titanium behaves no worse than stainless steel. It responds to cutting and pressure as well as does stainless steel. In an argon environment (atmosphere) and in a vacuum it takes a good weld. Titanium is now used on a production basis as is a long series of its alloys.

Titanium has two crystalline structures -- low temperature (α - a form existing up to 880 deg) and high temperature (a less dense β - a form stable up to the melting point). Its alloys also take various crystalline structures. Usually, the capacity of the metal exists in various crystalline forms attesting to the possibility of strengthening its alloys by heat treatment. Process titanium, consisting of only a 1% mixture, functions well to 350 deg C and conducts 20% less heat than aluminum. But, in spacecraft it is little used.

Introducing aluminum to a titanium alloy (2 - 8%) not only lightens it but retains the α-structure with high plasticity, increases the stability and corrosion stability during normal and increased temperatures. Such alloys weld well. Of them, for example, forged rings and various units for the *Mercury*, *Gemini*, and high-pressure containers for the *Apollo* were made. With a reduction of temperature, these alloys are noticeably hardened and do not become brittle.

The so-called α and β alloys are made of a mixture of granules of solid substances of greater stability and maintain this property to much higher temperatures. From the alloys of such types the frames of the *Minuteman* rocket engines were made, as well as fuel tanks, the oxidizer containers for the *Titan III*, and the high-pressure containers for cryogenic liquids for the *Atlas*, *Gemini*, and *X-15*

The most stable seems to be the heat-strengthened alloys in which the β-titanium structure is maintained even at low temperatures. It was from this that the shell and several panels of the *Mercury* were made.

BERYLLIUM. Berrylium (and its alloys) has an even higher specific stability in combination with exceptionally high rigidity which makes its use in spacecraft construction most favorable.

Being 4 times lighter than iron, beryllium exceeds the modulus of elasticity (the basic measure of the rigidity of a metal) of steel by 1.5 times, titanium by 2.5, and aluminum by 4 times. It exidyzes insignificantly to 600 deg C. For increasing its operation at even higher temperatures, the USA recently proposed a procedure for obtaining a chrome coating.

Beryllium has a higher thermal capacity than any other metal. In order to melt 1 kg of berrylium it is necessary to apply 3.3 times more heat than necessary to melt 1 kg of iron (Fig. 3).

From beryllium are made heat shields, rigid parts of inertial guidance systems, rigid units connecting spaceships with rocket systems, and many others (Fig. 4).

STEEL AND ALLOYS. Steel and alloys are basically composed of iron - the most stable and reliable material. The alloys are quite heat-resistant. But, steel is heavy: its density is 7.8 to 8.1 g/cm^3. In order that steel compete in space construction the alloys must be durable and highly processable. In recent years such steels were found. They are called steels of transitional Martensite-Austenite class. Their composition is very limited. Beside iron and carbon they contain nickel and manganese making it possible to obtain, when quickly cooled, the so-called austenite structure. As a result, the steels maintain a high plasticity and good weldability, but are less stable. If aluminum (or vanadium) is added, they tend to decompose to the austenite into martensite if exposed to extreme heat or cold; the plasticity is lessened but the stability increases. The limit of stability for the new steels reaches 160 - 350 kg/mm^2 (the specific stability is 20 - 40); i.e., like the titanium alloys but 5 times less expensive to produce.

STAINLESS STEEL AND OTHER HEAT-RESISTANT ALLOYS OF IRON, NICKEL, AND COBALT are widely used in aircraft and rocket engine construction as well as in the production of hypersonic flying craft. These materials have a stability of about 90 - 160 kg/mm^2 at normal temperatures, but are highly resistant to creep during prolonged heating to 800 to 1100 deg C and high viscosity at cryogenic temperatures. Parts of the *Mercury* capsule were made of cobalt alloy sheets and from the nickel alloy inconel which ensured the capacity for storing liquid nitrogen and oxygen on-board the *Apollo*. Strands of stainless steel were used for parachutes so as to parachute spacecraft back to earth. The thickness of these strands was 12 microns. The fabric retains a high stability up to 820 deg and only weakly oxidyzes when heated.

FIGURE CAPTIONS

Fig. 1. In this part of D.I. Mendeleyev's table are most of the light metals.

Fig. 2. The *Mercury* capsule. Three of its plates were prepared of a titanium alloy and the fourth was made of cobalt.

Fig. 3. The amount of heat expended in melting and vaporizing 1 kg of material.

Fig. 4. A heat absorber (a) and parts of the inertial guidance system (b) made of beryllium.