Abstract:
To be a versatile engineering material, a metal must offer a wide range in its mechanical properties to meet industrial requirements. Such a variation is accomplished in the mechanical properties of titanium by alloying and heat-treatment. Since neither one alloy nor one heat-treatment alone is capable of perfecting a metal with properties meeting all the demands of industry, alloying and heat-treatment have become major tools in the production of titanium materials.

Alloying

Research and development have shown that alloying can raise the tensile strength of titanium metal to more than 200000 psi (1380 MPa) while still maintaining useful ductility. The presence of interstitial elements, mainly carbon and the reactive gases of the atmosphere, also add strength to the metal but at the expense of severe loss in ductility. For simplicity the interstitial elements carbon, nitrogen, oxygen, boron, and hydrogen will be referred to as contaminants, and the substitutional elements, intentionally added, will be referred to as alloying elements.

Contaminants. Contaminants remain in titanium metal from incomplete purification in the reduction process or are absorbed in the melting practices employed. Iron in small qualities, 0.5 to 1%, appears to have a contaminating effect on ductility, but in larger quantities acts to influence the ductility no worse than other good substitutional alloying elements. The interstitials and iron are introduced in the sponge production reactions; in the melting practice, carbon, nitrogen, and oxygen contents may be further increased.

One major problem confronting both the sponge and wrought producer is to eliminate these impurities or at least keep them at a minimum. Present production of titanium metal has kept nitrogen and hydrogen contents, in general, below the critical combining quantity where reduction in ductility becomes marked. Hydrogen, carbon, oxygen, and, in some cases, iron, however, are still found frequently in titanium in proportions which are intolerable to the user.

Carbon and oxygen appear to have a combined effect on ductility and toughness. A low quantity of one will allow a greater toleration of the other. Large variations (0.03%-0.20%) have been noted in oxygen contents of commercially produced metal, and carbon contents up to 0.2% still result, although most titanium metal currently arc-melted is below 0.1% in carbon.

Nitrogen has been maintained generally below 0.05% in commercial production, and this quantity does not influence severely tile strength or ductility. With nitrogen contents above this, strength rises sharply and...
ductility falls off as severely as occurs with oxygen. The effect of boron, which is only slightly soluble in titanium, has not been thoroughly investigated.

Recently the titanium industry has become aware that hydrogen is a major factor in embrittling titanium. Most alloys cannot tolerate more than 200 parts per million of hydrogen, particularly if the material is to be subjected to fatigue or creep loading. Hydrogen can be substantially reduced by vacuum annealing, but this process does not lend itself to production economics.

Carbon, oxygen, nitrogen, and hydrogen, although they increase the strength of titanium, adversely affect the ductility and toughness so severely that these elements are kept at a minimum and are rarely employed as alloy additives.

**Alloy Additives.** To increase the strength of titanium metal and still maintain useful ductility, substitutional elements are employed. These elements replace titanium atoms in the lattice structure rather than situate in the voids between them, as do the interstitials.

By the utilization of basic physical metallurgical studies such as equilibrium diagrams of various alloy systems and by practical alloy development work, several substitutional elements have emerged as promising alloy additions. Manganese, aluminum, chromium, tin, iron, vanadium, and molybdenum in various combinations have been shown to lend versatility to tile mechanical properties of titanium metal.

These alloying elements increase the strength of titanium with an accompanying loss in ductility and toughness. The ductility and toughness, however, are far less influenced by these elements than by the contaminants, where increased strength is gained at a great sacrifice of ductility and toughness.

### Heat-treatment

The mechanical properties of titanium are more dependent on the phases present than they are on the actual composition of the alloy. Substitutional elements partially replace the titanium atoms in the lattice and in this manner alter the properties. In actuality, the amount of any and all phases present is better governed by the heating and cooling cycles than by this atom alteration.

Most alloy additives stabilize the body centered beta phase and lower the temperature of transformation to such an extent that at room temperature the alloys are a mixture of both the alpha and beta. The hexagonal alpha is relatively soft, tough, and ductile; whereas the beta is harder, stronger, but less ductile.

From this it can be seen that by changing the proportions of these phases, the mechanical properties can be varied. Many methods have been employed to produce the desired phase proportions, and from these have emerged five basic methods of heat-treatment: quenching, tempering, continuous cooling, isothermal transformation, and solutionizing and aging.

**Quenching.** If alloys are rapidly cooled by water quenching from the all beta region, the tendency of the alpha phase to form is suppressed, and the beta phase is retained. Certain alloy compositions, however, exhibit a peculiar transformation on quenching. This mechanism of martensitic or shear-like transformation is not completely understood. The formation of this structure, the so-called alpha prime, causes some distortion of the lattice. This distortion and the resulting strain produce a material, which is hard and tough, and possesses better fatigue properties than alpha. This quenching process is also the initial point for tempering.

**Tempering.** When titanium is quenched from an elevated temperature, reheated to a temperature below the beta transus, held for a length of time and again quenched, it is said to have been tempered. Three variables exist in tempering: the phases present, the time held, and the tempering temperature.

When the initial structure contains alpha prime, two changes occur: the alpha prime transforms to alpha, and at longer times the alpha becomes serrated. The result is a loss of hardness and strength and an increase in ductility and impact. Alpha-beta structures, however, do not follow this pattern. The alpha primarily remains unchanged; the beta decomposes to form more alpha at the expense of the beta phase. At low temperatures more alpha, will be...
formed; thus, low tempering temperatures result in a greater decrease in strength and hardness and a larger increase in ductility than the high temperature tempering over identical time intervals.

**Solutionizing and Aging.** If a titanium alloy is held in the beta or high in the alpha-beta region, quenched, and then reheated again to the alpha-beta region, it is said to have been solution-treated and aged. This treatment on titanium alloys produces much the same effect as tempering, with the exception that the initial structure is, for the most part, beta. Maximum hardness can be achieved in short-time aging, which is associated with the formation of a phase, referred to as beta prime. With longer times this beta prime is dissipated and alpha-precipitated, decreasing the hardness and resulting in better ductility.

**Isothermal Transformation.** On hot-quenching an alloy from the all beta region to temperatures in the alpha-beta field and holding for a period of time and then further quenching to room temperature, the material is transformed isothermally. Treatment in this way causes precipitation of the alpha phase from the beta. At high temperatures the alpha precipitates first at grain boundaries and later within the beta grains themselves.

This treatment, when holding at temperatures just below the transformation temperature, at first gives a very hard material due to formation of beta prime. If the time of holding is extended, the hardness and strength decrease with an accompanying increase in ductility and toughness. At lower temperatures a gradual rise in hardness and brittleness takes place, and at prolonged times a higher hardness may be obtained than by short time high temperature treatments.

**Continuous Cooling.** Continuous cooling is the lowering of the temperature of an alloy from the all beta field at any rate without interruption or subsequent reheating. Quenching, already discussed, is a specialized form of continuous cooling. The cooling rate, although not associated with one temperature, governs the interval of the transformation period. Rapid cooling rates suppress alpha formation and result in the beta phase being at least partially retained, which gives a moderately hard material. Slightly slower cooling rates result in a much harder and brittle metal of the same type previously referred to as beta prime. Slower rates give alpha-beta structures. The slower the rate, the greater the amount of alpha formed. As alpha increases, the ductility and toughness increase and hardness falls off.

When high hardness is the ultimate need, the material must be treated in such a way that the peak of the curve is reached. High hardness throughout the piece is best obtained by quenching a rich alloy, which falls to the left of the peak, and then tempering at low temperatures until the peak is reached.

When toughness is the prime factor, it is best obtained by quenching the lean alloys, which fall far to the right, from just below the beta transus. Such treatment gives low yield strength, but high impact strength. Some increase in yield strength can be obtained if these alloys are hot-worked in the alpha-beta region prior to quenching.