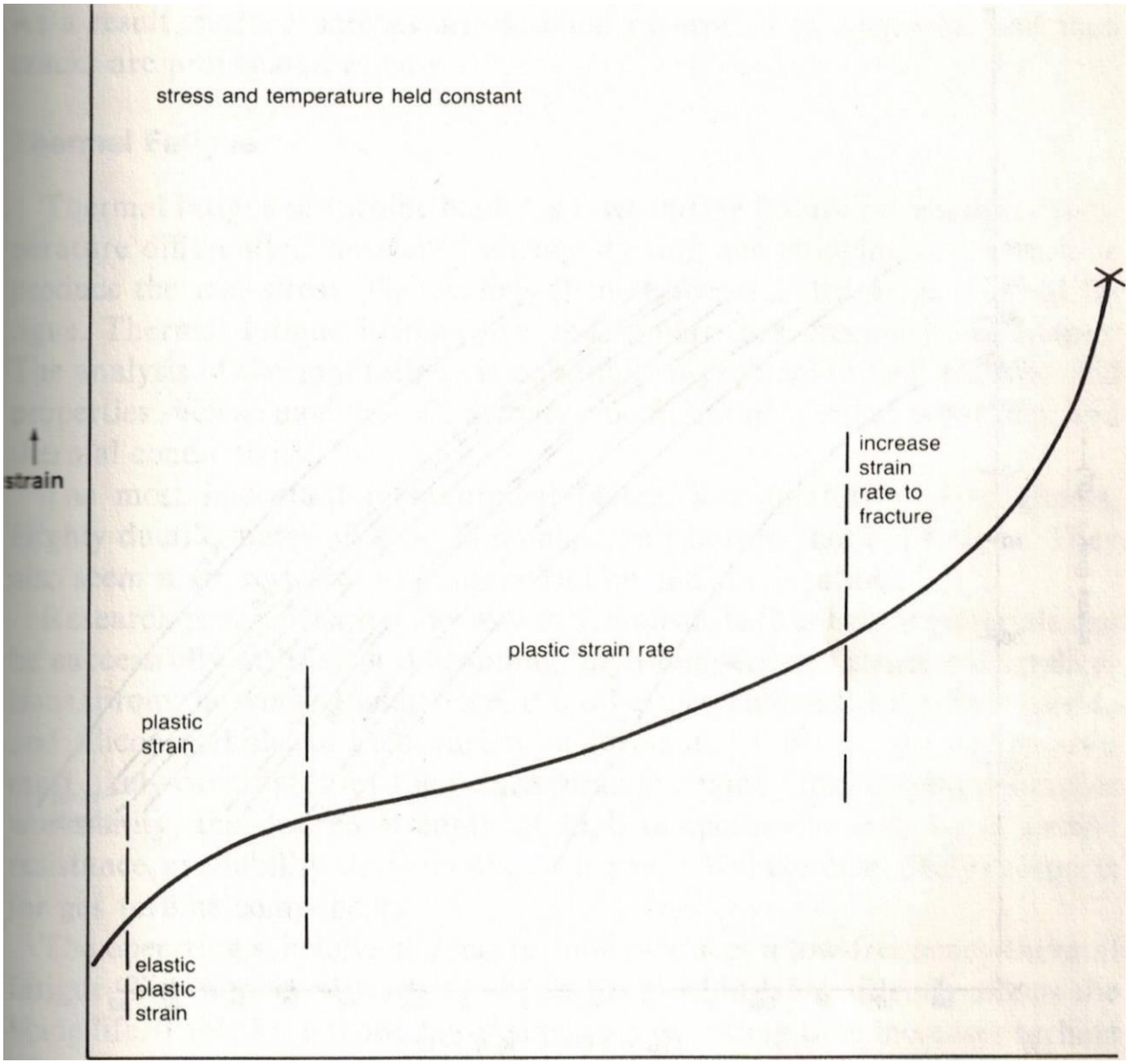
Metallurgical Behavior of Turbine Materials

Creep and Rupture

The melting point of different metals varies considerably, and their strengths at various temperatures are different.

At low temperatures all materials deform elastically, then plastically, and are time independent. However, at higher temperatures, deformation is noted under constant load conditions.

This high-temperature, time-dependent behavior is called creep rupture.



time —►

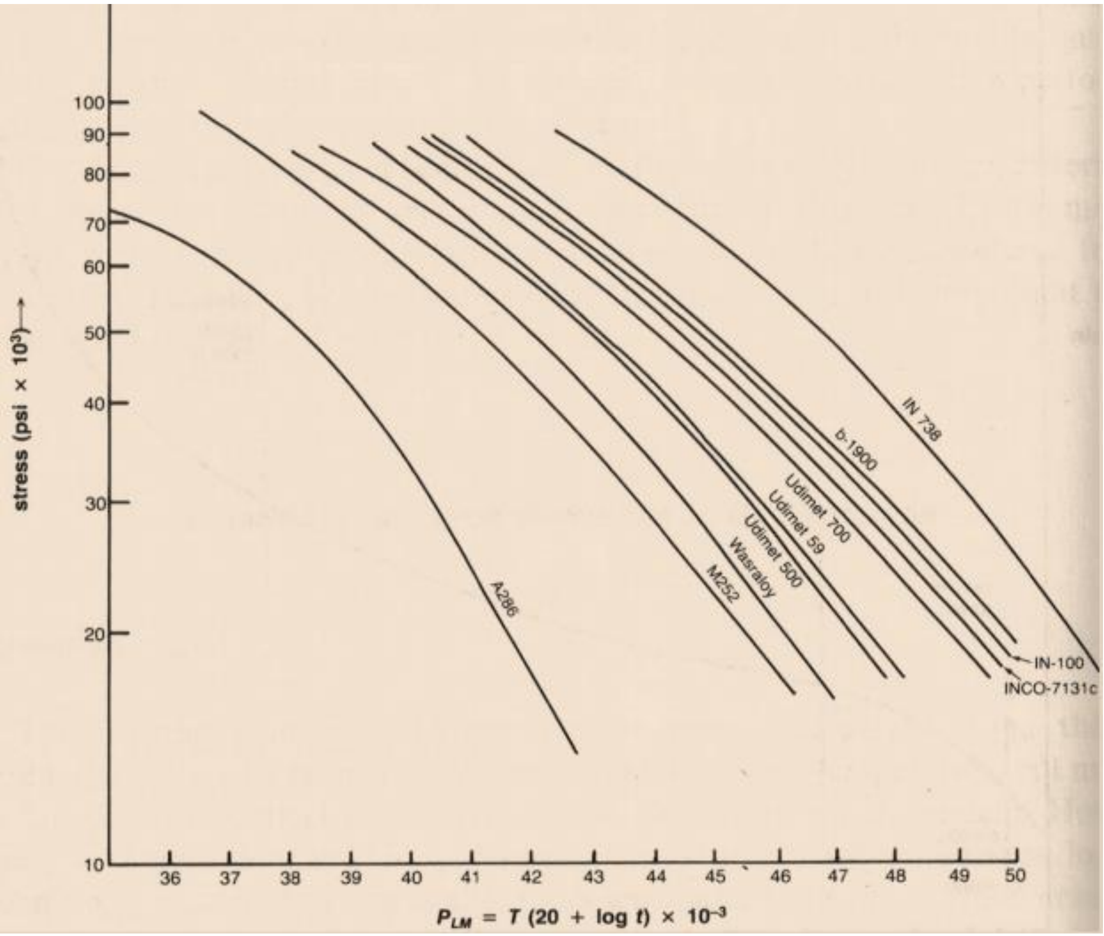
Figure . Time dependent strain curve under constant load

Figure above shows a schematic of a creep curve with the various stages of creep. The initial or elastic strain is the first region that proceeds into a plastic strain region at a decreasing rate. Then a nominally constant plastic strain rate is followed by an increasing strain rate to fracture.

The nature of this creep depends on the material, stress, temperature, and environment. Limited creep (less than 1%) is desired for turbine blade application. Cast superalloys fail with only a minimum elongation. These alloys fail in brittle fracture—even at elevated operating temperatures.

Stress-rupture data are often presented in a Larson-Miller curve which indicates the performance of an alloy in a complete and compact graphical style. While widely used to describe an alloy's stress-rupture characteristics over a wide temperature, life, and stress range, it is also useful in comparing the elevated temperature capabilities of many alloys.

The Larson-Miller parameters are plotted for the specified turbine blade alloys. A comparison of A-286 and Udimet 700 alloy curves reveals the difference in capabilities. The operational life (hrs) of the alloys can be compared for similar stress and temperature conditions.



Larson-Miller parameters for turbine blade alloys.

Ductility and Fracture

Ductility is commonly measured by elongation and reduction in area. In many cases all three stages of creep shown in Figure above are not present.

At high temperatures or stresses, very little primary creep is seen, while in the case of cast superalloys, failure occurs with just a small extension. This amount of extension is ductility.

In a time-creep curve there are two elongations of interest. One elongation is from the plastic strain rate, and the second elongation is the total elongation or the elongation at fracture. Ductility of a metal is affected by the grain size, the specimen shape, and the techniques used for manufacturing. A fracture which results from elongation can be of two types: brittle or ductile, depending on the alloy. A brittle fracture is intergranular with little or no elongation. A ductile fracture is trans granular and typical of normal ductile tensile fracture. Turbine blade alloys tend to indicate low ductility at operating temperatures.

As a result, surface notches are initiated by erosion or corrosion, and then cracks are propagated rapidly.

Thermal Fatigue

Thermal fatigue of turbine blades is a secondary failure mechanism.

Temperature differentials developed during starting and stopping of the turbine produce thermal stress. The cycling of these thermal stresses is thermal fatigue. Thermal fatigue is low-cycle and similar to a creep-rupture failure. The analysis of thermal fatigue is essentially a problem in heat transfer and properties such as modulus of elasticity, coefficient of thermal expansion, and thermal conductivity.

The most important metallurgical factors are ductility and toughness. Highly ductile materials tend to be more resistant to thermal fatigue. They also seem more resistant to crack initiation and propagation.

From the study already done, it has been established that silicon nitride and silicon carbide, in their variety of forms and fabrications, are the two most likely candidates for the future ceramic engine. Both exhibit a suitable workability, the desired strength at high temperatures, and have specific resistance, availability, and manufacturing ease to make them likely prospects for gas turbine components.

The operating schedule of a gas turbine produces a low-frequency thermal fatigue. The number of starts per hours of operating time directly affects the blade life. Fewer starts per operating time increases turbine life.

Corrosion

The use of Ni-base superalloys as turbine blades in an actual end-use atmosphere produces deterioration of material properties. This deterioration can result from erosion or corrosion. Erosion results from hard particles impinging on the turbine blade and removing material from the blade surface. The particles may enter through the turbine inlet or can be loosened scale deposits from within the combustor.

Corrosion is described as hot corrosion and sulfidation processes. Hot corrosion is an accelerated oxidation of alloys caused by the deposition of Na_2SO_4 . Oxidation results from the ingestion of salts in the engine and sulfur from the combustion of fuel. Sulfidation corrosion is considered a form of hot corrosion in which the residue that contains alkaline sulfates. Corrosion causes deterioration of blade materials and reduces component life.

The corrosion problem includes: (1) erosion, (2) sulfidation, (3) intergranular corrosion, and (4) hot corrosion.

The 20% Cr alloys increase oxidation resistance. 16% Cr alloys (Inconel 600) are less resistant. Cr in alloys reduces grain boundary oxidation, while high Ni alloys tend to oxidize along grain boundaries. Age-hardened gas turbine blades of 10-20% Cr will corrode (sulfidation) at more than 1400°F. Ni2S forms in the grain boundary.

The addition of cobalt to the alloy increases the temperature at which the attack occurs. To reduce corrosion, either increase the Cr amount or apply a coating (Al or Al + Cr).

A high-nickel alloy is used for increased strength at elevated temperature, and a chromium content in excess of 20% is desired for corrosion resistance.

An optimum composition to satisfy the interaction of stress, temperature, and corrosion has not been developed. The rate of corrosion is directly related to alloy composition, stress level, and environment. The corrosive atmosphere contains chloride salts, vanadium, sulfides, and particulate matter. Other combustion products, such as NOX, CO, CO2, also contribute to the corrosion mechanism. The atmosphere changes with the type of fuel used. Fuels, such as natural gas, diesel #2, naphtha, butane, propane, methane, and fossil fuels, will produce different combustion products that affect the corrosion mechanism in different ways.

Superalloys for GT

Most nickel-based superalloy developmental efforts have been directed towards improving the alloy high temperature strength properties with relatively minor concern being shown to its hot corrosion resistance. Further, it is not always possible to achieve both high temperature strength and hot corrosion resistance simultaneously because some alloying elements help to improve hot corrosion resistance while some may help to improve high temperature strength. It is rare that an alloying element leads to enhancement both in high temperature strength and the hot corrosion resistance simultaneously.

This is further complicated for marine applications by the aggressivity of the environment, which includes sulfur and sodium from the fuel and various halides contained in seawater. These features are known to drastically reduce the superalloy component life and reliability by consuming the material at an unpredictably rapid rate, thereby reducing the load-carrying capacity and potentially leading to catastrophic failure of components.

Thus, the hot corrosion resistance of superalloys is as important as its high temperature strength in marine gas turbine engine applications. Recent studies have shown that the high temperature strength materials are most susceptible to hot corrosion and the surface engineering plays a key role in effectively combating the hot corrosion problem.

It is important to mention that chromium is the most effective alloying element for improving the hot corrosion resistance of superalloys. In order to obtain good resistance to hot corrosion, a minimum of 15wt% chromium is often needed in nickel-based superalloys and a minimum of 25wt% chromium in cobalt based superalloys. The results clearly revealed that all the studied superalloys are highly vulnerable to hot corrosion.

Effects of alloying elements

From the present results, it is concluded that the new superalloy is highly susceptible to hot corrosion, though it exhibits excellent high temperature strength properties. It is clear that other superalloys are also vulnerable to both types of hot corrosion. It stresses the need to apply high performance protective coatings for their protection against hot corrosion both at low and high temperatures i.e. type II and type I as the marine gas turbine engines encounter both the problems during service. The protective coatings allow the marine gas turbine engines to operate at varied temperatures and enhance their efficiency by eliminating failures during service. Research in this direction has resulted in design and development of smart coatings which provide effective protection to the superalloy components for the designed period against type I, type II hot corrosion and high temperature oxidation that are normally encountered in gas turbine engines which in turn enhances the efficiency of gas turbine engines considerably.

Titanium Alloys

Unlike the conventional / existing coatings, the smart coatings provide total protection to the superalloy components used in aero, marine and industrial applications by forming appropriate protective scales like alumina or chromia depending on the surrounding environmental conditions

The titanium alloy components experience hot corrosion problem when they are used for marine gas turbines. It severely limits the high temperature capability of alloys in terms of mechanical properties. It is important to mention that the depth of the titanium alloys affected in marine environment is about 100 times more than that of the alloys corroded in other environments at the same temperature. It clearly indicates the greater aggressiveness of marine environments to titanium alloys compared to other environments.

Reference: Gas Turbine Engineering Handbook, M.P.Boyce