INTRODUCTION

Titanium is the 4th most abundant metal in the earth's crust, with an estimated ore reserve of 2140 million tons. Titanium and its alloys fill the density gap between aluminium and steel. They possess high specific strength, excellent corrossion resistance and attractive high temperature properties. The metal is youngest among the engineering metals, and among the non-ferrous metals it has the widest range of alloys developed to meet very specific and stringent applications in a broad spectrum of industries. However, the high energy and complex technology required to extract, melt and process titanium makes it relatively more expensive, thus limiting its applications. Despite the high cost, titanium and its alloys have proved their versatility as engineering materials for a variety of applications including aerospace, chemical, petro-chemical and power generation industries.

The titanium industry assumes special signficance in our national context. India is endowed with large reserves of titanium minerals, estimated[1] at 130 million tonnes of ilmenite and 7.0 million tonnes of rutile, amounting to 10% of the world reserve. The Indian Rare Earths (IRE) and Kerala Mineral and Metals Limited (KMML) have production plants at Tamilnadu and Kerala for producing pigment grade Ti-dioxide (TiO_2). While the technology for melting and fabrication of titanium into various components already exists in the country, titanium is yet to find its rightful place in the national industrial scene. One reason is that, India lacks the facility for production of the virgin metal. The present requirement of titanium and its alloys in the country is estimated[2] at 200 tonnes/annum for the next two years and the requirement is expected to reach 500 tonnes/annum by 1989-90. The estimated break up of demand sectorwise is shown in Table 1.1.

TABLE 1.1 ESTIMATED DEMAND OF TITANIUM IN INDIA[2]

SECTOR	1986 - 87 (TONS)	1989 - 90 (TONS)
AERONAUTICS	40	100
SPACE	10	20
DEFENCE	-	100
CHEMICAL, PETROCHEMICAL AND GENERAL ENGINEERING	120	200
POWER GENERATION	35	100
	205	520

Although titanium is beginning to find increased applications in chemical and other industries due to its high corrosion resistance, the aircraft gas turbine engine has been the main driving force behind much of titanium alloy development work. The extensive alloy development programmes in the 1950's and 1960's were mostly dedicated to meet the requirements of the aero-space industry. The aircraft designers required low density-high strength alloys with good creep resistance at elevated temperatures for the fabrication of compressor blades and alloys with deep hardenability and fracture toughness for compressor discs. Titanium provided them with an optimal choice.

The physical and electronic properties of titanium atom provide a large scope for producing a wide range of alloys with vastly differing mechanical properties (see Chapter 2). A favourable atomic size enables titanium to form solid solutions with a large number of alloying elements. The occurance of the allotropic phase change from high temperature β phase (bcc) to the room temperature α phase (hcp), the strong dependence of the transus temperature on the alloy composition and variety of phase transformations present in titanium base systems permits careful microstructural control to tailor properties to specific requirements (see Chapter 3).

The need to improve the creep capability and the useful service temperature of titanium alloys was one of the main driving force behind much of the alloy development work. A number of new alloys with increasing creep strength have been developed (Fig. 1.1), leading to increase in temperature capabilities of titanium alloys from 350°C to around 590°C over the last two decades[3]. These last two decades

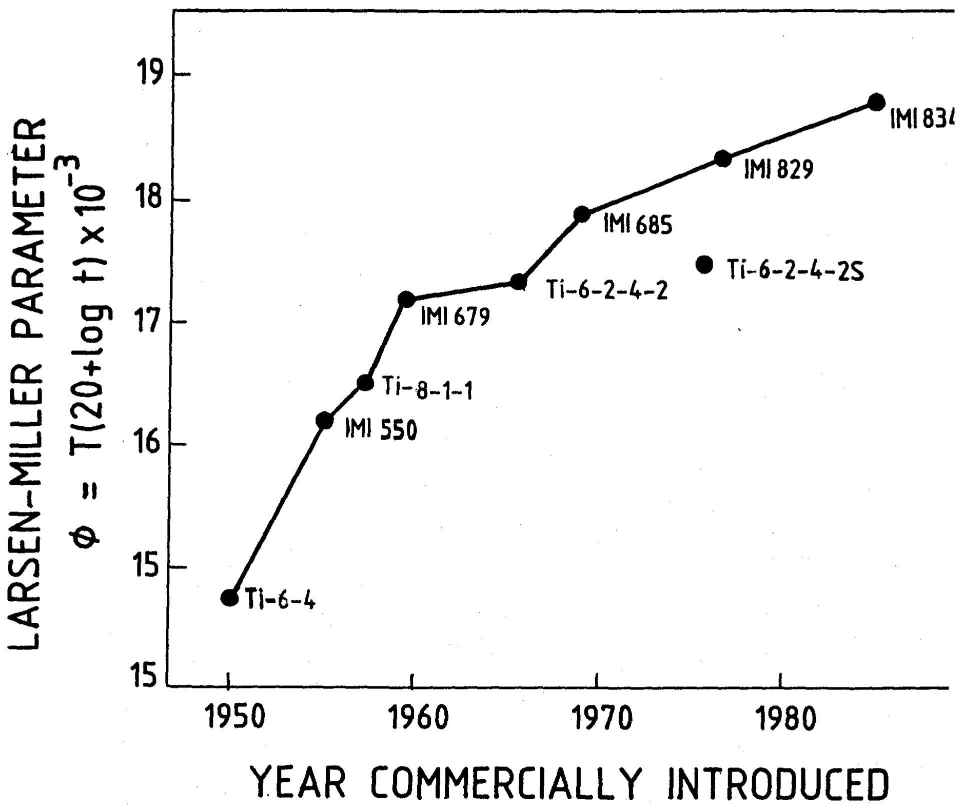

FIG. 1.1: CREEP RESISTANT TITANIUM ALLOY DEVELOPMENT: Year of development and Larsen-Miller parameter.

have seen the evolution of two simple criteria on which high temperature alloy design can be based (Chapter 3). The first of these determines the composition of the alloy based on Rosenberg's α equivalent[4]. The hcp α phase by virtue of its closed packed structure exhibits lower diffusivities and hence superior in creep resistance to the bcc β phase. However, solid solution strengthening of the α phase by addition of α stabilising elements is limited to a maximum, beyond which the Ti_3Al based intermetallics precipitate, making the alloy brittle. The α phase can not be strengthened by solid solution alloying beyond a limit. Hence small volume fraction of the β phase (typically about 5% in near α alloys) are stabilised and strengthened by alloying.

The second criterion relates to the microstructure: Creep resistant titanium alloys were earlier processed and heat treated in the $\alpha+\beta$ phase regions, to develop a microstructure consisting of equiaxed primary α grains within transformed β matrix. Recent studies show that β annealed alloys, consisting of accicular α microstructure, exhibit a superior combination of creep resistance[5], fracture toughness[6] and fatigue crack growth resistance properties[7]. The beta heat treated structure is however not desirable for high temperature strain control low cycle fatigue (LCF), because, enhanced oxidation along the phase boundaries leads to premature crack initiation along surface connected lamellar interfaces[8]. Further it is also associated with low ductility.

A list of titanium alloys currently used in gas turbine engines in aircrafts is shown in Table 1.2. All of these alloys essentially belong to the $\alpha+\beta$ or near α composition and have additions of both α and β stabilising elements.

TABLE 1.2 TITANIUM ALLOYS USED IN CURRENT GAS TURBINE ENGINES

ALLOY TYPE	COMPOSITION	TEMPERATURE LIMIT (°C)	APPLICATION
	Ti-6Al-4V (IMI 318)	350	DISCS, BLADES & STATIC PARTS
ALPHA + BETA	Ti-4Al-2Sn-4Mo-0.5Si (IMI550)	450	DISCS & BLADES
	Ti-6.4Al-2.7Mo-1.6Cr-0.2Si (VT 3-1)		
	Ti-6Al-2Sn-4Zr-6Mo (Ti-6-2-4-6)		
	Ti-6.5Al-3.5Mo-2Zr-0.25Si (VT - 9)		
NEAR ALPHA	Ti-8Al-1V-1Mo (Ti-8-1-1)	400	BLADES
	Ti-6Al-2Sn-4Zr-2Mo (Ti-6-2-4-2)	450	DISCS, BLADES & STATIC PARTS
	Ti-6Al-11Zr-1Mo-1Nb-0.1Si (VT - 18)	500	
	Ti-6Al-5Zr-0.5Mo-0.25Si (IMI 685)	520	
	Ti-5.5Al-3.5Sn-3Zr-1Nb-0.25Mo-0.3Si (IMI 829)	540	

Despite these improvements that have been made, the useful service temperature of titanium alloys are disappointingly low relative to its high melting point. Some promise for overcoming this shortcoming is provided by Ti-Al based intermetallics - Ti_3Al and TiAl. The interest in the aluminides, whose development was pioneered by Kornilov, is based on their excellent high temperature properties, which are comparable to the nickel base super alloys,but they have much lower density than nickel base alloys. The aluminides however have poor hot workability and extremely low ductility at ambient temperatures, restricting their use. Research is going on all over the world to ductilise these alloys. However much more development work will be needed before they can be used in the aircraft engine. Hence, at present and in the coming two to three years, the creep resistant titanium alloys will be mainly based on the 'Near α ' compositions.

This thesis is concerned with the high temperature composition Ti-6.5Al-3.3Mo-1.6Zr-0.3Si. Only a few references in the literature deal with the physical metallurgy of this alloy. These, moreover, are almost exclusively concerned with the $\alpha + \beta$ processed and heat treated condition. Chapter 4 describes the melting and processing of the alloy and various testing procedures followed in this thesis. The first aim of this study is to examine the effect of processing and heat treatment on microstructure development in the alloy (vide Chapter 5). The β heat treatment and its effect on microstructure development has been studied in exhaustive detail.

Chapter 6 provides a broad overview of the influence of the microstructure developed (as described in Chapter 5) on mechanical properties such as tensile strength, yield strength, tensile ductility and creep rupture. Qualitative explanations are proferred for the role of various microstructural features in determining these properties. Consistent with earlier observations in the literature, it is found that the β heat treatment confers superior creep properties while decreasing tensile ductilities in this alloy as well.

The discussion in Chapter 3 indicates structure-property relationships in the $\alpha+\beta$ processed and heat treated conditions have been evaluated in great detail. Comparatively little work has been carried out for the β heat treated condition. The interrelationship between microstructure, deformation behaviour, fractographic features and tensile ductility in the β heat treated condition of the alloy therefore forms the subject matter of Chapter 7. The main parameter varied in the heat treatment is the cooling rate subsequent to solution treatment.

Finally, Chapter 8 examines the effect of β treatment on creep behaviour of the alloy. Since Si is believed to play a major role in determining the creep strength of titanium alloys (see Chapter 4) two compositions of the alloy have been examined, one without Si and one with the nominal Si content. The use of stress change experiments, following specific types of β heat treatments and the examination of crept dislocation structures by TEM have been used to clarify the precise role that Si plays in imparting creep strength to β heat-treated Ti alloys.

A concluding chapter (Chapter 9) summarises the results and provides directions for future research in these areas.