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Casting of Titanium and its Alloys

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Abstract. Titaniuni and its alloys have many applications in aerospace, marine and other engineering industries. Titanium requires special melting techniques because of its high reactivity at elevated temperatures and needs special mould materials and methods for castings. This paper reviews the development of titanium casting technology.

1. Introduction

Because of the high reactivity of titanium at elevated temperatures, technology for its winning, melting and processing is rather complex[1]. Material recovery in the fabrication of components by conventional thermo-mechanical processing is of the order of 10 to 20 per cent. From liquid metal, casting provides the shortest route to final shape and ensures much higher material utilisation and cost effectiveness* (Fig. 1). A complex casting like the one illustrated in Fig. 2, can replace a multi-piece assembly or weldment, often with substantial improvement in both quality and appearance and that too at a much lower cost[3]. However, at present castings constitute only one per cent of the total titanium product@.

Problems in melting and casting of titanium arise from its great chemical reactivity with crucible and mould material and its affinity for atmospheric gases. The present practice of mould making includes rammed graphite moulding and investment moulding with refractory metal coats[5'6]. Cast components upto 700 kg have been produced in rammed graphite moulds for chemical processing industries' and investment castings weighing upto 30 kg have been produced for critical aerospace and biomedical appli-

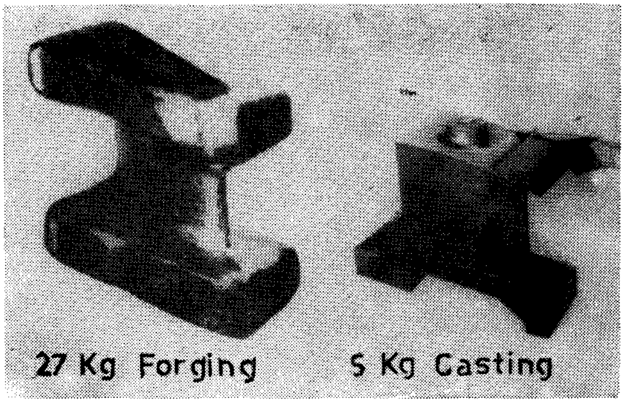

Figure 1. Relative amounts of titanium required for making an aircraft component by forging and casting route, (Left-27 kg forging, right-5 kg casting).

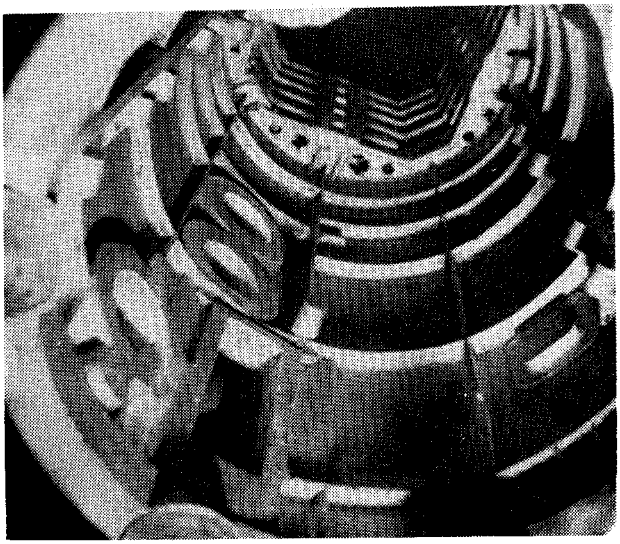

Figure 2. Sectional view of a cast magnesium missile body.

cations[8]. A few examples of these castings are given in Fig. 3. The investment cast parts cost 200 to 300 dollars per kg whereas parts cast in graphite cost 50-150 dollars per kg”. Recently zircon sand moulds have been used with very encouraging results for small titanium castings at US Bureau of Mines’” and Defence Metallurgical Research Laboratory (DMRL), Hyderabad[11]. An experimental casting of radiographic quality produced at DMRL is shown in Fig. 4. Wrought titanium alloy compositions can be cast without significant problems, although centrifugal methods are sometimes necessary for optimum filling of the moulds. It is also learnt that hitherto difficult to process titanium aluminides are now being investment cast into compressor blades for an engine development programme in the United States.

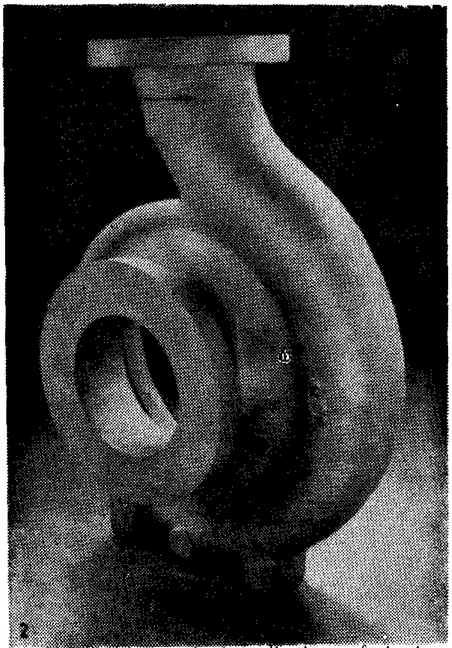

Figure 3. (a) **Typical** applications of titanium castings : Pump body for chemical process industry.

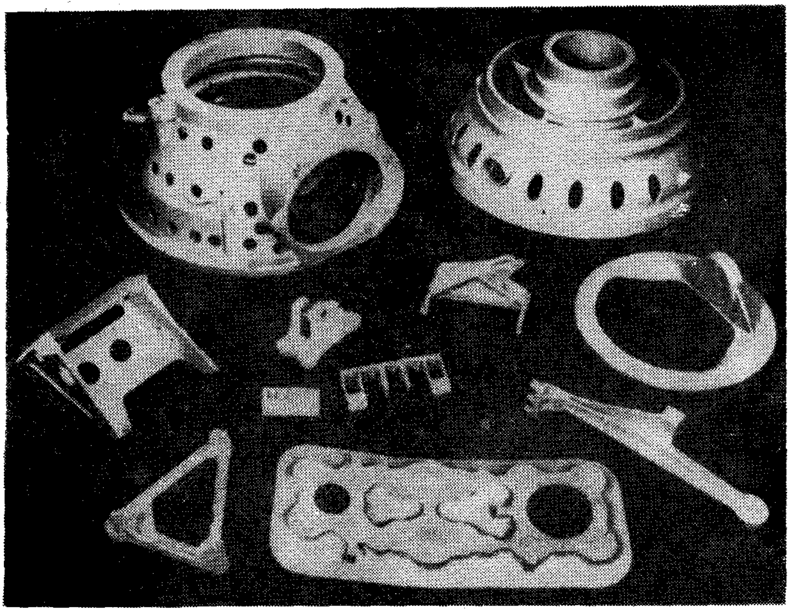

Figure 3. (b) Typical applications of titanium castings : Complex precision castings for aerospace applications.

The cast titanium generally has transformed beta structure which is associated with superior creep resistance, fracture toughness, fatigue crack growth resistance and

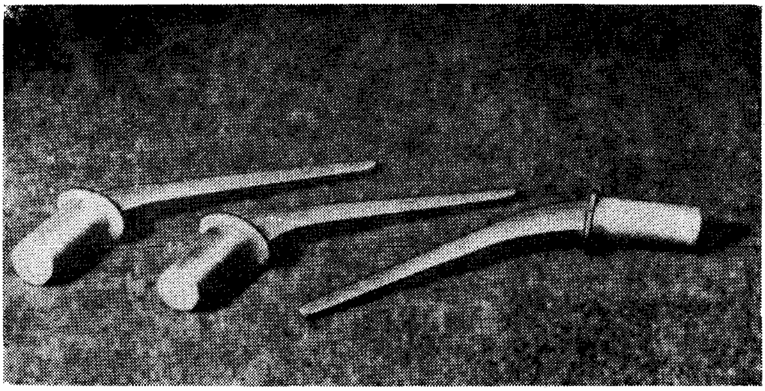

Figure 3. (c) Typical applications of titanium castings : Biomedical applications-HIP prosthesis.

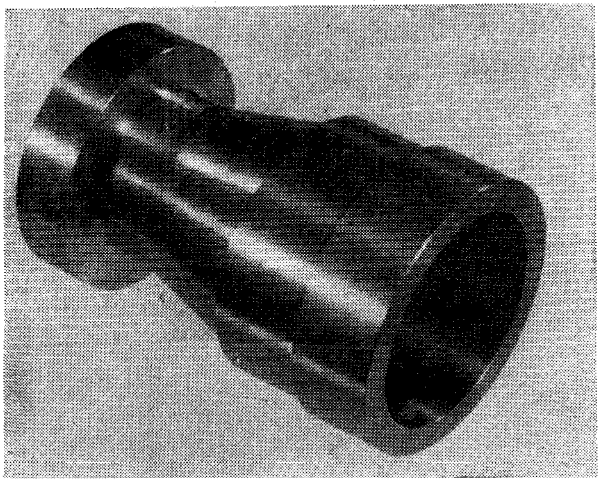

Figure 4. Titanium component cast in zircon sand mould in DMRL.

tensile properties[2,13]. But the titanium castings exhibit lower fatigue strength due to the presence of internal porosities[14]. These porosities can now be healed by hot isostatic pressing for improved properties[15,16]. The titanium castings will find much wider applications with the development of economical methods of melting and moulding and availability of better casting alloys. This paper reviews the methods of melting and casting, moulding practices, cast alloy systems and properties.

2. Metal Mould Reactions

Most stable refractory oxides such as stabilized zirconia, calcia and alumina react with titanium to produce a skin which is enriched in oxygen or intermetallic compounds of titanium. Reactions between molten titanium and simple oxide mould materials can be grouped into two categories :

(1) ***Type*** 1 (simple ***dissolution)--The*** oxide dissolves in liquid titanium giving rise to a contaminated skin.

$$M_2O_3 \rightarrow 2M_{Ti} + 3O_{Ti} \qquad (1)$$

The dissolved elements may precipitate as separate phase on cooling.

(2) ***Type II (formntion of sub-oxides and intermetallics***—Molten titanium will react with less stable refractory oxides to form sub-oxides and intermetallics containing titanium.

For example,

$$n/2\ SiO_2 + m\ Ti \rightarrow TiO_n + Si_{n/2}\ Ti_{m\ n} \qquad (2)$$

Ternary and higher order refractory oxides undergo changes in composition in addition to dissolution of one or more component oxides with or without formation of lower oxides and intermetallic compounds of titanium.

Fortunately, because of the low specific heat of titanium per unit volume, the interface between molten metal and mould coolsr apidly during casting, and the reactions do not proceed to equilibrium. However, significant reactions are known to occur leading to contamination of the surface of castings. Weber, et al[17] have summarized the work up to 1957 on the reactivity of molten titanium with container materials and recommended oxygen deficient zirconia as a crucible material. Eastwood & Craighead[18] have examined a large number of refractory compounds and metals and concluded that with the possible exception of zirconia, all were reactive. Garfinkle & Davis[19] found CeS to be the most resistant material to attack, although dissolution of the sulfide was observed. A number of binary and ternary oxides, carbides and nitrides were tested by US Bureau of Mines[10,20]. In these studies, thermodynamic consideration were used by comparing the free energy of formation of refractory compounds with corresponding titanium phases (TiO, TiO_2, TiN, TiC). But no material could be identified to be inert to molten titanium though some were less reactive[17-20] (Table 1).

It is possible to have moulds with inexpensive back up materials and a face-coating having high resistance to liquid titanium, because of the short time exposure of mould to liquid metal during casting. But designing a crucible material for molten titanium by itself is a formidable task.

3. Melting and Casting

Over the last thirty-five years a number of melting methods have been used for titanium e.g., induction, vacuum arc and electron beam melting. Of these, only vacuum arc and

Table 1. Materials least reactive to molten titanium

Oxides	Y_2O_3, ThO , Gd_2O_3, CeO_2, $La_2O_3.ZrO_2$ Nd_2O_3, ZrO_2 + 5-10 wt CaO or Y_2O_3 MgO, $MgO.Al_2O_3.ZrO_2$, $Al_2Zr_3O_9$ $Al\ O_3$ + 10 wt Y_2O_3, $BaZrO_3$, $MgZrO_3$ and $CaZrO_3$
Fluorides	CaF_2
Carbides/Nitrides	ZrC, NbC, B_4C, BN and Pyrolitic graphite
Metals	*Mo, Ta, W*
Back up materials	Molochite, fused silica, SiC, and graphite

electron beam melting methods are commercially used though efforts continue for developing other methods to achieve better control on melting and higher utilisation of scrap.

3.1 *Induction Melting*

Kura[21] described an experimental tilting furnace which uses a graphite crucible heated by high frequency induction. Dupont[22,23] developed larger graphite furnaces of 400 kg capacity with bottom pouring system. Simon[24] used a rotating graphite crucible for forcing the liquid metal up into the moulds attached to it. In all these methods, melt was contaminated with carbon beyond acceptable limits.

Recent studies[25,26] have indicated that Yttria (Y_2O_3) is a potential crucible material for vacuum induction melting of titanium although it suffers from two drawbacks viz inadequate thermal shock resistance and interaction with titanium. The problem of thermal shock resistance was partially overcome by using laminates, with alternate layers of Tungsten and Yttria prepared by plasma spraying[27]. However, the metal was contaminated with 0.7-0.9 per cent Yttria precipitates.

A novel inductoslag method for melting titanium is under development at US Bureau of Mines[28,29]. The induction melting is done in a water cooled copper crucible with longitudinal segments which interrupt the induced current flow. The crucible is lined with CaF_2 to avoid shorting arising from running of the molten metal between the segments. One such crucible shown schematically in Fig. 5, is 125 mm in diameter with 32 segments and has a pouring capacity of 4 kg of titanium?“. The advantages include relatively simple operation, better control of melting and pouring rates and superheating the metal to about 50°C. But entrapment of CaF_2 in the metal stream is a major disadvantage.

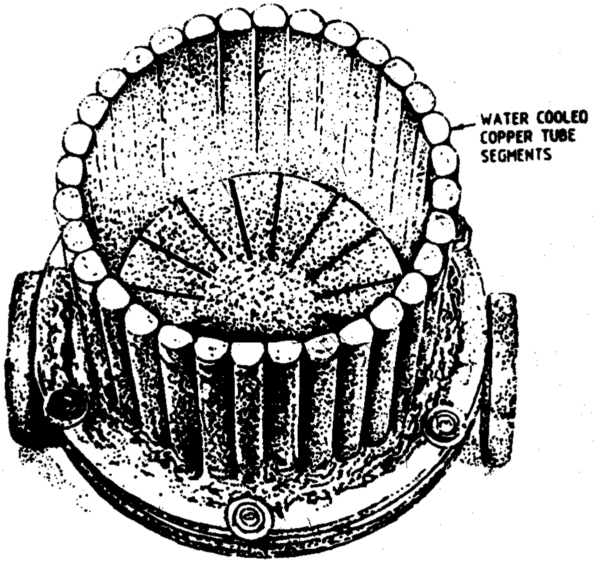

Figure 5. Inductoslag titanium casting crucible of 125 mm dia. with thirty-two segments.

3.2 Arc Melting

US Bureau of Mines[30,31] has developed a skull casting process using consumable arc melting in a tiltable water cooled copper crucible, as shown in Fig. 6. The titanium electrode is melted at a high current density (400-800 amps per centimetre of crucible in vacuum) and melting rates of the order of 5-15 kg per minute are achieved[32,33]. The water cooled crucible maintains a thin layer of skull at all times and prevents contamination of the melt by the crucible. When a desired amount of metal builds up in the crucible, the electrode is rapidly retracted and the melt is immediately poured into the mould. About 15 per cent of titanium is retained as skull, though the pouring sequence is completed within a few seconds”. In most of the cases, titanium is cast centrifugally to overcome the problem of fluidity which arises due to lack of superheat.

3.3 Electron Beam Melting

High power electron beam technology was developed in the fifties for the production of niobium metal and nickel base super alloys[34,35]. Subsequently this technique was used for melting and casting of titanium alloys[36,37]. This method uses a stream of energetically charged particles flowing from a tungsten or tantalum cathode further accelerated by a high voltage (20-40 KV). Electron beam melting has an advantage over arc melting in that input power can be controlled independent of the melting rate. Other advantage is that the electron beam can be directed to heat the pouring metal to

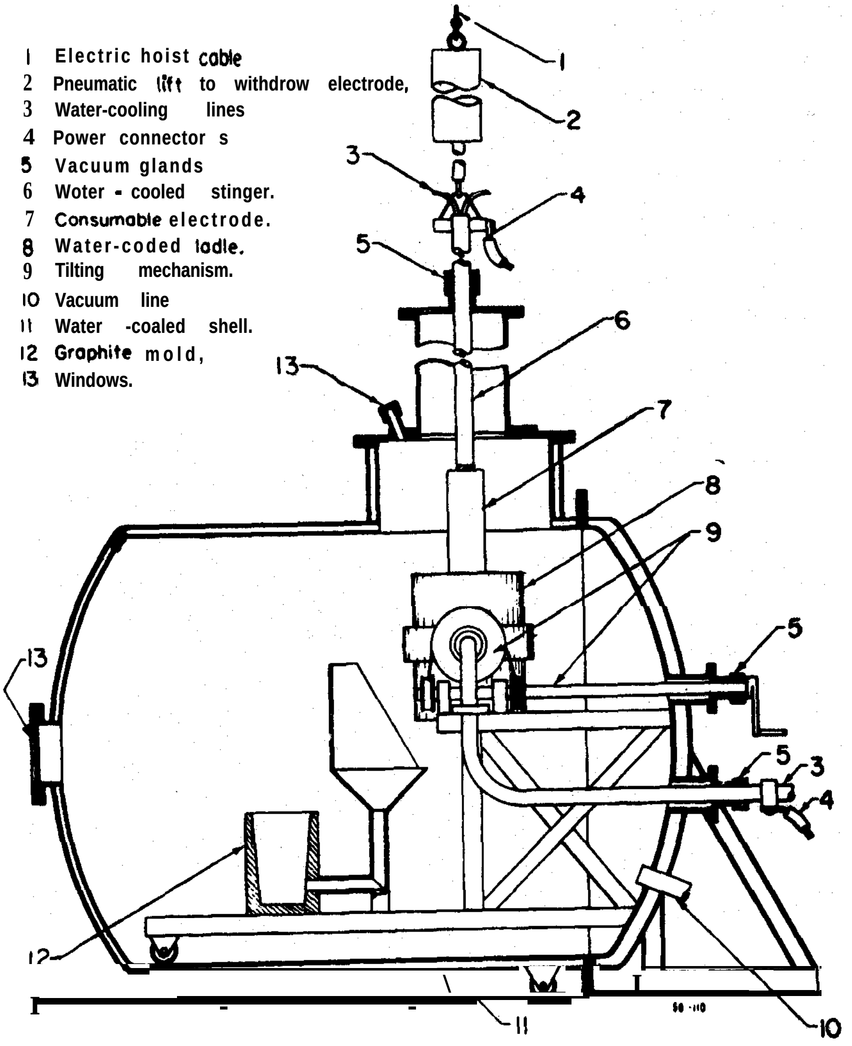

Figure 6. Consumable arc skull casting furnace using externally cooled copper crucible.

a desired temperature or/and hot top the risers. But a high vacuum during melting causes loss of alloying elements which have high vapour pressure e.g. Al and *Mn*.

4. Mould Materials and Systems

Titanium has a high melting point and a low thermal conductivity which gives rise to a steep thermal gradient in the metal during solidification. The reaction with mould produces an embrittled surface zone containing oxygen, carbon nitrogen or other elements picked up from the mould. The contamination of the surface seriously affects the mechanical properties and dimensional accuracy of the castings. The contaminated zone is generally called 'alpha case' and its thickness depends on the chemical stability of the mould material and period of contact between liquid titanium and the mould. If the molten metal cools rapidly, the surface contamination can be minimised. However, rapid solidification tends to affect adequate feeding of metal into the mould sometimes resulting in cold shuts, gross porosity and centre line shrinkage.

4.1 Graphite Moulds

Kroll[38] suggested graphite as a suitable mould material for titanium. The high thermal conductivity of graphite results in rapid solidification of the molten metal at the mould interface forming a strong contaminated skin which restricts further metal-mould reaction. The reaction zone can be removed by machining or chemical milling. Initial development work was based on machined graphite moulds but now most of the industrial castings are produced in rammed graphite moulds developed by Field[39] and Beal[40] independently. In this process graphite powder along with suitable binders and surface activating agents are mulled together. The moulding mixture is then rammed hard around a wood or metal pattern. Later the pattern is removed and the mould is cured. Different rammed graphite moulding methods developed[39-42] are summarised in Table 2.

Shell moulds in graphite were developed by Westword[43] using high purity graphite powders and about 40 per cent phenolic resin. This moulding mixture, along with suitable solvents is invested to a conventional shell mould pattern and heated to a temperature between 480-560°K to produce a shell of thickness 1 to 2 mm. The shell moulds are subsequently heated to 1170K for about 2 hrs. in an inert atmosphere.' Titanium castings produced by this process are reported to be superior to those produced using machined graphite moulds.

4.2 Sand Moulds

Among the common foundary sands, zircon ($ZrSiO_4$) is the only material that can be used for titanium casting. Zircon has a fusion point of 2700K with good flowability, relatively high conductivity and better dimensional stability than graphite. In addition zircon sand moulds have been used for many years in ferrous and nonferrous foundries with good results for heavy walled premium castings. Malone[44] reported that molten titanium reacts violently with zircon but later studies by Lang, et al[45] reported that zircon rammed moulds using sodium silicate as binder withstood the attack of molten titanium. But casting of thickness of 12 mm or more produced in the above moulds suffered from pinholes and poor details. Koch[10] used sodium silicate in lower quantities and reported very good results in castings upto 100 mm cube size. He also tried a number of mould washes and found that zirconia wash with a water or isopropyl alcohol base is very effective for inhibiting metal-mould reactions. Bentonite has been tried as a binder since it produces excellent grain strength and good dry

Table 2. Different Methods used for Rammed Graphite Moulding

Field[39]	**Beal**[40]	Ausmus & **Beal**[41]	**Pukonik**[42]
53% Graphite (– 20 + 100)	Granular graphite	Granular Graphite	Graphite powder AFS fineness 45-55 (100 parts)
10% corn starch	Corn starch	Corn starch	
10% pulverized pitch	Cereal binder	Cereal binder	Flux Binder (20parts)
8% **carboneceous** cement	Petroleum pitch	Dextrine	Starch or
1% Surface active agent (Duponol G-fatty alcohol) (amine sulphate)			sodium silicate (2-5 parts) water 10%
18% water		**Muled** in CO, **atmosphere**CO_2 accelerates setting of Linseed oil	
Oven dried, temperature increased gradually from 330K to 393K for 48 hrs. Fired between 923K to 1172K for 1-2 hrs.		Air cured at ambient temperature for 24-48 hrs before drying at 473K for 4-5 hrs. Open molds are then fired at 1173-1273K in reducing atmosphere or vacuum for h-12 hrs. and furnace cooled	Bake at 532K for 4-8 hrs + brief torch heating of mould cavities

strength in rammed zircon moulds. This combination indicated good results in castings of 150 mm cube size[46].

In a recent study at DMRL[11] zircon sand was used with CO, moulding method for casting titanium. Here sodium silicate is used as binder and hardened by CO_2 gas which releases collodial silica as given in the simplified reaction.

$$Na_2\,Si,\ O_5 + H_2\,0\ (I) + CO,\ (g) = Na_2\,CO_3 + 2SiO_2 + H_2O\ (1) \qquad (3)$$

The zircon moulding composition was standardised with respect to sodium silicate addition and curing temperature (Fig 7) to obtain moulds with enough strength and required collapsibility[47]. These moulds also exhibited good permeability. In this study it was observed that increasing the addition of ZrO_2 in zircon sand decreases the surface contamination which is apparent from the hardness values[47] plotted in Fig. 8.

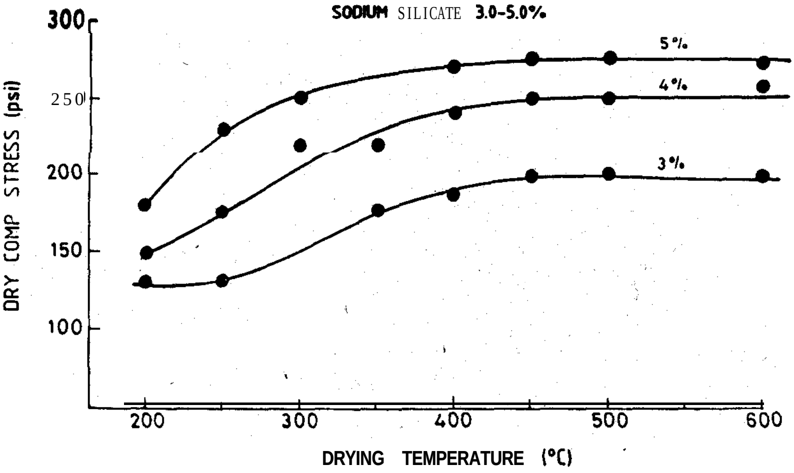

Figure 7. Effect of curing temperature on zircon mould strength.

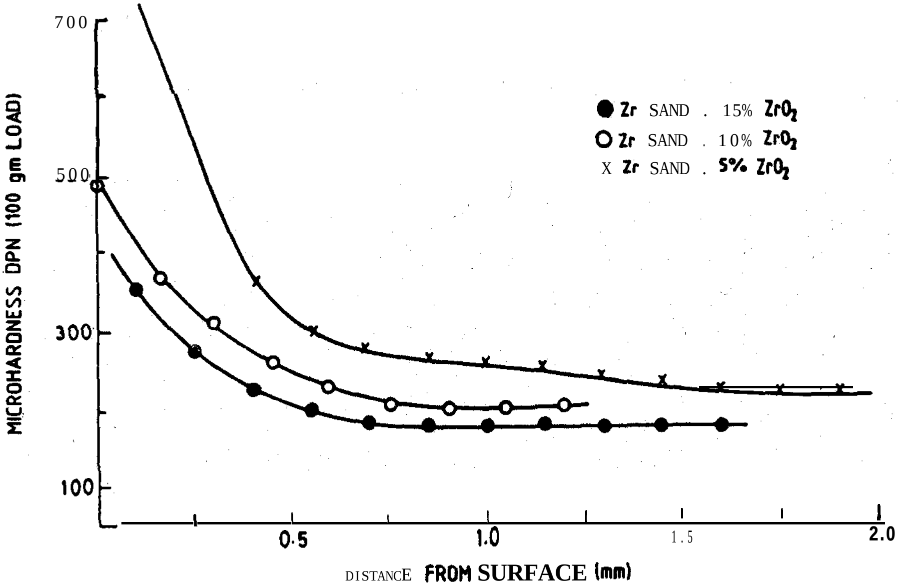

Figure 8. Effect of zirconia addition on surface hardness of titanium castings.

4.3 Investment Mould

The investment moulding technique is employed to produce high quality intricate castings requiring high dimensional accuracy.. This method is also known as lost wax process[48,49]. A typical wax pattern, investment shell and cast parts are shown in Fig. 9. The surface of titanium castings is contaminated with oxygen, to a depth upto 0.75 mm

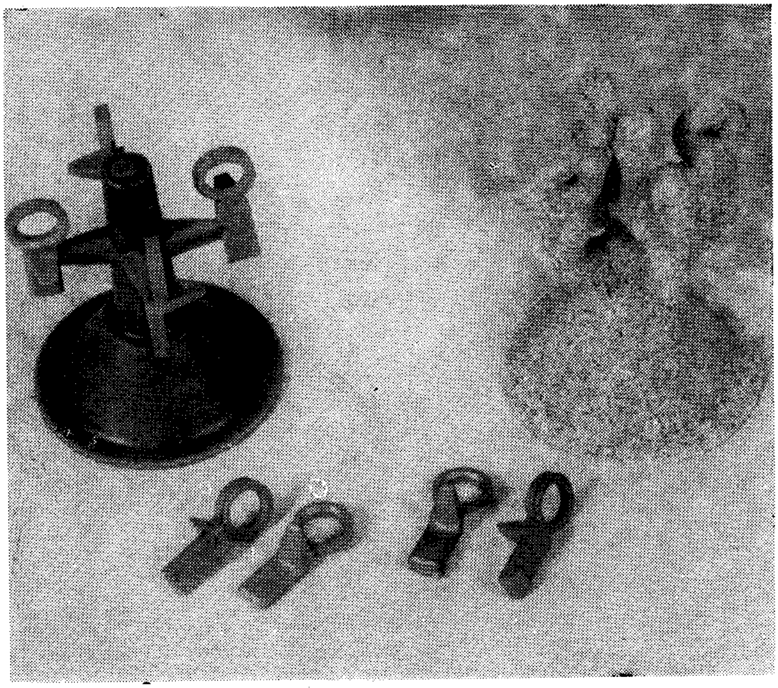

Figure 9. Investment cast parts : (a) Wax pattern with pouring and gating system, (b) Investment shell, and (c) Investment cast parts.

in 25 mm sections when conventional refractory oxides and binders are used in preparing investment shells, resulting in embrittlement[50]. Oxide folds and embedded non-metallic inclusions are also present on the surface of castings. But use of thoria, calcia or zirconia base moulds has resulted in castings with minor surface contamination.

An investment moulding method which employs refractory metal (W, *Ta, Nb* or Mo) facing[6] is reported to give a contamination free surface in casting up to 35 kg. In this process the wax pattern is washed in a mixture of organic solvents to ensure satisfactory adhesion of the metallic layer. Application of this layer is carried out by immersing the wax pattern in a slurry consisting of finely divided refractory metal powder, an inhibitor-former and a metal-organic binder under controlled conditions. When the pattern is taken out, stucco is sprinkled on it by a special sprinkling equipment. The pattern is dried and the intermediate and backing layers are applied by conventional investment methods. The precise combination of mould materials, binders and casting techniques are considered proprietory[51,5]. The mould must be dried under a controlled temperature and moisture condition. Since the binders used with the facing layers are hygroscopic, dewaxing is done in two stages using tetrachloroethylene. After dewaxing the moulds are dried in an air circulation oven at 540°K and then fired under dry hydrogen at 1373°K in a retort furnace.

A similar method based on graphitic slurry known as Monograf process was developed by **Howmet**[53]. In this process the wax assembly is dipped into the graphitic slurry and then in a bed of stucco alternatively until a shell of required thickness is formed. The shell is dried, dewaxed and fired. The completed mould is impregnated with a resinous binder or a densifier and refired. Castings weighing up to 25 kg have been produced by this process with close tolerances of ± 0.005 cm and a high degree of surface finish (90-125 rms).

4.4 *Mould Coatings*

Suitable candidates of mould coatings must possess a high melting point, be satisfactorily inert to liquid titanium, be non-hygroscopic and have a reasonable cost. Reeves and Chapin[54] studied the effect of barrier coatings on machined graphite moulds to improve their chemical stability. The coatings were applied either by oxy-acetylene or plasma spray technique. Out of several oxide coatings they found that calcium zirconate ($CaZrO_3$), Gd_2O_3 and Y_2O_3 were resistant to molten titanium with no significant increase in either carbon or oxygen content. The barrier coatings were not effective in altering the heat extraction pattern of the graphite substrate.

An investment shell or a solid ceramic mould can also be coated by pyrolytic graphite or by carbon using proprietory process in which the mould is heated in an atmosphere containing hydrocarbons[55-57]. During coating, the parameters such as gas composition, flow rate, pressure, and mould temperatures are varied to suit the size and shape of the mould. Prior to pouring, the moulds are preheated in vacuum. Metal mould reactions occur forming thin layers of titanium carbide of varying thicknesses (0.05 - 0.5 mm) depending on the section size.

The advantage of these coating methods is that the basic mould or core is produced by conventional investment moulding technique and then coated with less reactive materials.

4.5 Segmented Mould

One of the most striking developments in precision investment casting technology has been the segmented mould process, originally developed by TRW, Inc., (U. S. Patent No. 4,043,379; 4,066,116 and 4,170, 256). In this process the desired casting geometry is sub-divided into a number of segments, each segment having its own pattern. Each pattern has a thick rigid internal metal chill and a flanged parting line, which allows the mould to be split. During dewaxing the mould splits along the parting line. The chill is removed and the interior of the mould is inspected for defects and dimensional stability. The defective segment can be rejected resulting in minimum repair and rejection of castings. Each segment mould can be tailored for its solidification requirements and accordingly mould material or coating can be selected for minimised reaction and optimum heat flow to give improved soundness and surface finish. This way very large moulds can be built up from small segments.

5. Casting Defects and Repair

Titanium castings exhibit common casting defects like shrinkage, gas porosity, cold shuts and misruns. The surface defects such as surface connected porosity or cold shuts can be weld repaired. The defect area is blended with surrounding metal, cleaned and then filled with weld metal under argon atmosphere. Internal porosities which include shrinkage porosities and spherical shaped gas porosities are of major concern. These porosities can be limited by suitably designing the gating and risering system[47,58] but can now be completely healed by hot isostatic pressing where the casting is subjected to simultaneous application of argon gas pressure (1000-1500 MPa) and temperature (1100-1300K) in a HIP unit’“. During HIPing voids and porosities collapse by creep or plastic deformation and the collapsed surfaces get diffusion bonded creating a fully dense homogeneous casting (Fig 10).

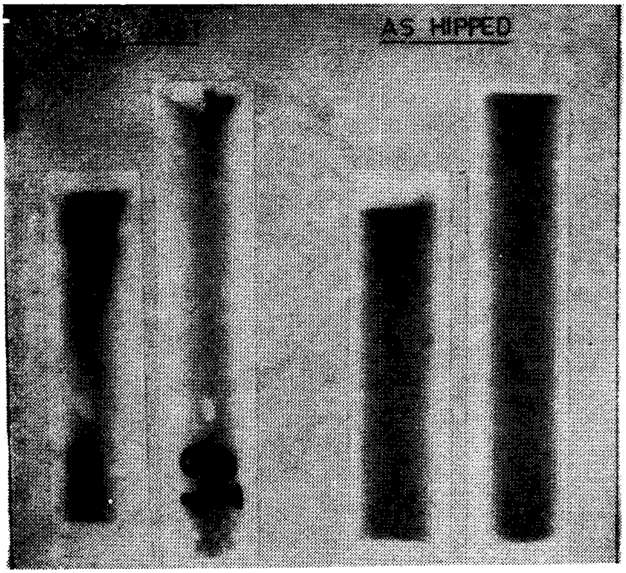

Figure 10. Healing of internal porosities in titanium cast bars by HIPing.

6. Casting Alloys and their Properties

6.1 *Alloy Systems*

In general, titanium is a good base for cast alloys formulation. It is characterised by a relatively high fluidity and its resistance to cracking due to hot shrinkage. Rate of solidification in the mould is 3.4 mm $sec^{-1/2}$ which is somewhat higher than that of steels[59]. For titanium, shrinkage is about 1.5 per cent in ceramic moulds and 2 per cent in steel moulds[61]. Eylon[9] has summarised a number of titanium alloys used for castings which are basically wrought alloys (Table 3). Magnitazkii[61] has studied the effect of various elements on castability and concluded that elements which increase the solidification range adversely affect the fluidity and increase the amount of shrinkage porosity. The elements which increase the heat of fusion will improve the fluidity. *Al*, *Cu*, *Fe* and *Mn* additions decrease viscosity, while *Sn*, *Co* and *V* do not affect it. However, small additions of *Zr*, *Ni*, *Nb*, *Mo* and *Si* decrease viscosity initially but the viscosity increases with further additions. Magnitazkii[59] established a relation to calculate the fluidity which is given as

Table 3. Titanium Alloys used for producing Castings

Alloy	Class	Remarks
CP-titanium	Oxygen levels and minor alloy additions constitute different grades	Corrosion resistance, chemical and energy applications
Ti-6Al-4V	Alpha-beta alloy	The most commonly used alloy for aero-space and chemical applications
Ti-6Al-6V-2Sn	Medium-strength alpha-beta alloy	Used in higher strength applications than *Ti-6Al-4 V*
Ti-6Al-2Sn-4Zr-2Mo	Near-alpha, high-temperature alloy	Wrought material contains some *Si* for higher creep resistance
Ti-6Al-2Sn--4Zr-6Mo	Alpha-beta, high-strength alloy	For engine rotating components requiring higher strength than *Ti-6242*
Ti-6Al-2Sn-2Zr-2Mo-2Cr-O. 25Si	Deep hardenable alpha-beta alloy	Intended for use in applications requiring some deep hardenability
Ti-5Al-2.5Sn	Alpha alloy	Good cryogenic properties and highly weldable.
Transage 175 (*Ti-2.5Al-13 V-7Sn-2Zr*)	Deep hardenable. martensitic alloy	High-strength alloy, strain transformable
Ti-10 V-2Fe-3Al	Near-beta forgeable alloy	High strength, good fracture characteristics
Beta *III* (*Ti-11.5Mo-6Zr-4.5Sn*)	Metastable beta alloy	High strength, ductility deep hardenable
Ti-Cu alloys	Low-melting-point alloys	Experimental casting alloy
Ti-5Al	Alpha alloy	Used extensively in USSR for castings

$$\Lambda = A\left(\frac{Q_k}{T_k}\right)^{0.4}\left(\frac{\Delta T_k}{T_k}\right)^{0.6}\left(\frac{\Delta T_3}{T_k}\right)^{0.4}\left(\frac{T_3 - T_\phi}{T_3}\right)^{-1} C_{cp}^{0.7}\,\lambda_*^{0.6}\,\lambda_m^{-0.9}\,\eta^{-0.1} \quad (4)$$

where

Q_k = heat of crystallisation, T_k = liquids temperature, A T_k = crystallisation temperature range, T_3 = metal temperature, A T_3 = metal super heat, $T\phi$ = mould temperature, C_{cP} = volume heat capacity, λ_* = heat conduction of liquid metal, λ_m = heat conduction of solid metal, η = toughness.

Early attempts at development of eutectic type cast titanium alloys were not very encouraging since very high alloying additions resulted in high densities and also brittle alloys.[60], [62], [63] But in a recent study, Bomberger, et al. [64] obtained high ductilities in near eutectic cast composition of *Ti-Cu* system as shown in Fig. 11. They also studied the effect of additions like *Fe, Ni, Co* on the strength and ductility of *Ti-Cu* alloy. The development of titanium alloys based on eutectic compositions may make induction melting possible in suitable crucibles, because of their low melting point.

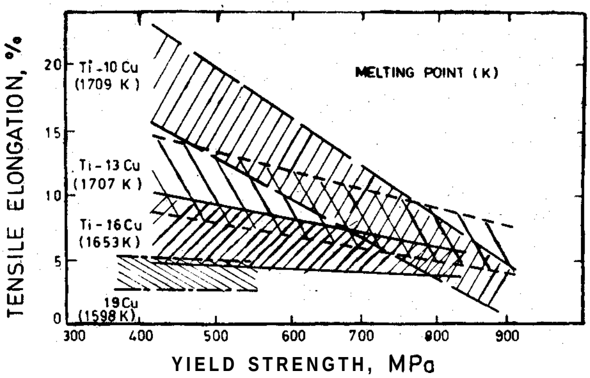

Figure 11. Yield strength and ductility of titanium-copper and titanium-copper-X alloys.

6.2 Microstructure

In case of alpha and alpha + beta titanium alloys, cast microstructure is acicular with alpha needles or platelets occuring in a basketweave pattern as shown in Fig. 12(a). Residual beta phase is also present between the alpha platelets in case of these alloys as shown in Fig. 12(b). The exception to this structure would be the case of highly beta-stabilised titanium alloys where the beta phase is retained and the alpha phase

Figure 12. Typical microstructures of different grades of titanium alloys: (a) Cast structure of a near alpha titanium alloy (*Ti*-11), (b) Retained beta phase present between alpha platelets in an alpha-beta titanium alloys (*VT*-9), and (c) Alpha precipitation in retained beta grains in a beta titanium alloy (Beta C).

precipitates on ageing as shown in Fig 12 (c). In the basket weave type structure, the acicular alpha phase has a high aspect ratio which provides extended interface for crack propagation resulting in higher energy absorption during crack propagation. Further, prior beta grain size, colony size and thickness of platelets affect the mechanical properties. In general, this microstructure exhibits improved strength, creep and fatigue properties but somewhat lower ductility.[65-67] The prior beta grain size can be reduced by micro additions of rare earth metals and oxides for improved properties[68]. Very fine microstructure is also possible by controlled heat treatment[69] and hydrogenating practices[70] in cast parts.

6.3 *Mechanical Properties*

Titanium castings exhibit mechanical properties comparable to those of wrought products and it is generally not the case with other metallic alloy systems. Even the specifications for titanium castings call for strength levels equal to those of equivalent wrought titanium compositions but with slightly lower ductility". Mechanical properties of a number of titanium alloys in the cast and heat treated conditions are summarised in Table 4. Eylon[9] has compared fatigue data of various workers on titanium wrought and cast products as shown in Fig 13. Titanium castings exhibit somewhat lower fatigue strength as compared to wrought products probably due to the presence of internal porosities.[13,14]

As mentioned earlier, the properties of castings can be improved by subjecting them to HIPing cycle. Significant improvement in tensile ductility is observed without any adverse effect on strength level[15] (Fig. 14a) in case of *Ti*-6*Al*-4*V* casting when HIPed (900°C, 105 MPa for 2 hrs). The closure of internal porosities results in higher fatigue strength at 5 million cycle for *Ti*-6*Al*-2*Sn*-4*Zr*-2*Mo* casting as shown[16] in Fig. 14(b). HIPing also reduces scatter in properties and thus ensures greater reliability of titanium castings in highly stressed critical service applications.

Table 4. Typical room temperature mechanical properties of several cast titanium alloys (Condition : Cast and annealed)

Alloys	Tensile strength (MPa)	Yield strength (MPa)	Elongation (%)	Reduction in area (%)	Charpy Impact (J)	Typical notch rupture strength in 5 hrs. (MPa)
Commercial pure titanium	550	450	17	32		
Ti-6Al-2Sn-4Zr-2Mo	973	876	12	20	39.4	1242
Ti-6Al-4V	980	883	11.5	18.5	25.8	1173
Ti-6Al-6V-2Sn	1152	1090	4	9.5	17.7	1380
Ti-3Al-8V-6Cr-4Zr	1132	1076	4	7	8.2	1242
Ti-2Al-13V-7Sn-2Zr	793	759	5.7	11		
Ti-11.5Mo-6Zr-4.5Sn	1132	1076	4	7	8.2	1242

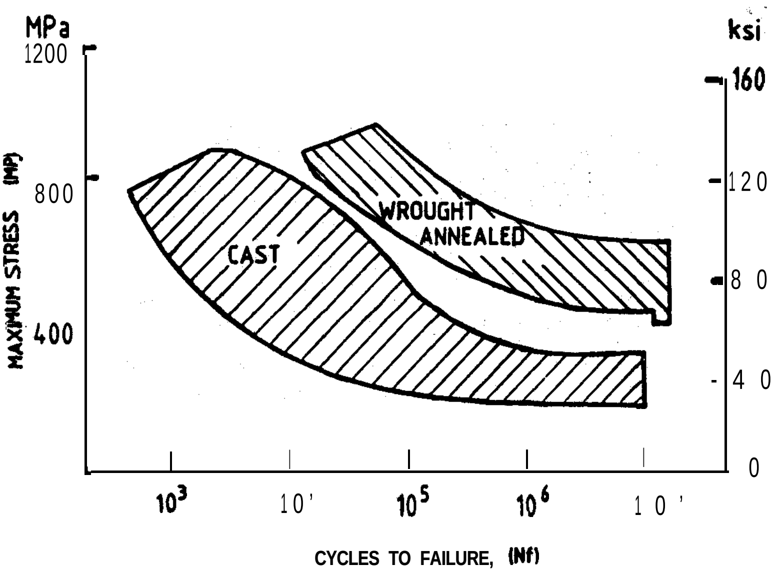

Figure 13. Room temperature smooth axial fatigue life for cast and wrought *Ti-6Al-4V*.

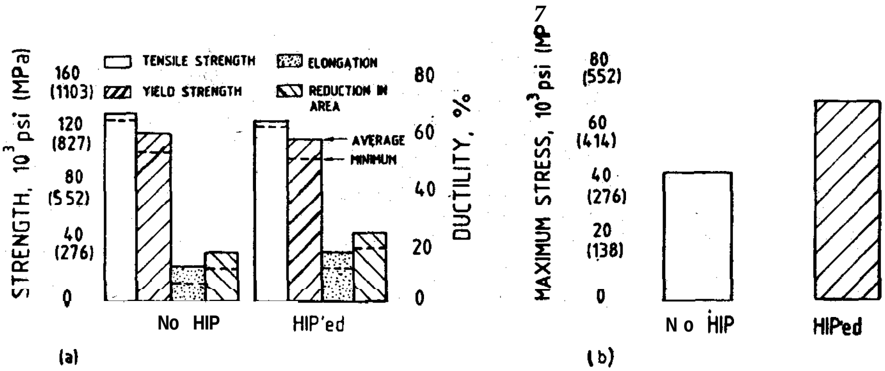

Figure 14. Effect of **HIPing** on mechanical properties : (a) Improvement in tensile properties of *Ti-6Al-4V*, and (b) Improvement in fatigue strength of *Ti-6Al-2Sn-4Zr-2Mo* at 5 million cycle life.

7. Development of Titanium Casting Technology in India

Research and development efforts on various aspects of titanium technology are continuing since last fifteen years in the country. At the Defence Metallurgical Research Laboratory, Hyderabad, research has been initiated to develop the titanium casting technology indigenously and encouraging results have been obtained with zircon sand moulds. At the Indian Institute of Science, Bangalore, theoretical studies based on thermodynamical analysis have been undertaken on design and selection of suitable mould and crucible materials resistant to molten titanium.

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