APPLICATIONS OF TITANIUM AND TITANIUM ALLOYS

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Introduction

At the time of the last Titanium Conference at Kyoto in 1980, the titanium industry was experiencing the largest ever demand for titanium, mainly from aerospace markets. Despite the general world recession, the aircraft industry was still buoyant, and saw an urgent need for airlines to replace old and comparatively inefficient aircraft, and to re-equip generally. As far as the UK was concerned, Rolls-Royce were supplying RB 211 engines for a wide range of aircraft, but especially the -524 for Tristar. The RB 211-535 had also been chosen as the launch engine for the Boeing 757. In addition, military aircraft building was going on apace with major projects such as the Jaguar, Tornado, etc.

The picture has changed dramatically since then. The past four years have continued to be overshadowed by the worst economic recession which any of us can remember. There has been a serious downturn in the fortunes of the civil aircraft industry, with many of the world's airlines in severe financial difficulties. In consequence, markets for new airframes, engines and equipment have been weak. Lockheed have decided to abandon Tristar building, and there is fierce competition between Boeing and Airbus Industries for the remaining wide-body market. However the signs are now better. A significant and progressive feature of the last few years has been the international co-operation between aerospace producers, both in engines and airframes.

Military aircraft programmes are still going ahead at about the same rate, and discussions are in progress in Europe on the initial design of a new aircraft to succeed the Jaguar and Tornado. There is however no project in Europe like that of the B1 bomber in the USA, of which 100 aircraft will be delivered under the initial contract, and which uses large volumes of titanium in both airframe and engine. Nevertheless, joint programmes with the USA on the AV8B Harrier for the US Marine Corps and the Hawk trainer for the US Navy, should provide welcome markets for titanium products in engine and airframe manufacture.

Furthermore, the financial performance of the airlines has been much improved in recent years, and new orders for aircraft have begun to be placed. Future predictions vary on the level of business or the volume of air traffic, but it has been estimated that 5000 new aircraft out of the present world fleet of 6300 (of 45,000 lb empty weight and over) will be replaced. The majority of new aircraft delivered will include those currently in production, such as Boeing 737, 747, 757, 767; Douglas DC9 and 10; Airbus 300 and 310. In addition, a large demand is forecast for the "150 seater". The volume of air traffic is forecast to grow by between 5.5-6% p.a. (US) and 7.5% p.a. (outside US).

As far as the titanium industry is concerned, the destocking of recent years, coupled with a modest increase in demand, has caused lead-times for mill products to be extended in the last few months. Thus, although we have still not recovered to the levels of 1980, we can look even to the short-term demand with more confidence than would have been possible 2 or 3 years ago.

Aerospace Applications

Contrary to some expectations, which have suggested that only a general growth in size or number of aircraft would enhance the titanium market, the proportion of titanium in aero-engines and airframes is still increasing. The reasons for this are that the fuel savings from improving the performance of fans, compressors etc, often produce benefits out of proportion to the apparently small numbers involved. Two of the most important ways in which titanium has contributed are improvements in high temperature creep resistant alloys or design of component, and development of fabrication techniques such as superplastic forming and diffusion bonding, which lead to reduced costs of manufacture as well as to improved performance.

Aero-engines

The use of titanium alloys in gas turbine engines has grown to the point where they can account for as much as 25% of the weight of the latest large fan engines, in which the major applications continue to be fan and compressor discs and blades, ducts and casings.

One of the most significant recent developments in design of fan has been the wide chord fan blade introduced by Rolls-Royce in its RB 211-535 E4 engine, chosen as the launch engine for the Boeing 757 (Fig. 1). The shape of these blades, made from IMI 318, and which are about 40% wider in chord than solid blades, makes them strong enough to resist flutter and fatigue without the support of mid-span "snubbers". The elimination of snubbers allows the whole area of the blade to be effective without interrupting the flow of air. Since approximately 75% of the thrust of a high-bypass ratio turbofan comes from the fan, the benefits of the wide chord blade are considerable, about 4% more efficient, equivalent to around 2.5% lower sfc than the solid bladed fan on the 535C engine. Another benefit is that only 22 blades are needed to make up a fan, compared with 33 solid blades in the 535C engine. Although the weight saving on the 535 is not great, because the fan is relatively small in diameter, the design could be much more significant on larger engines.

A particular feature of the blades is that they are "hollow". Solid blades were not acceptable because of the weight penalty of a casing strong enough to contain a blade failure, as well as a heavier fan.

Although the last few years have seen improvements in the properties of titanium alloys, the most widely used material in engines and airframes continues to be 6Al-4V. Applications in engines include fan discs and blades in the large fan Rolls-Royce RB 211 series of engines, the General Electric CF6, and Pratt & Whitney JT9D and 2037 engines. It is also used for lower temperature applications in the compressor stages of advanced military engines, such as the Turbo-Union RB 199. Other alpha-beta alloys used for lower temperature operation include IMI 550 (Rolls-Royce Pegasus and Olympus 593), Ti-6Al-2Sn-4Zr-6Mo (Pratt & Whitney F100), and Ti-17 (Ti-5Al-2Sn-2Zr-4Cr-4Mo, used by General Electric in the F404 military

Fig. 1: Titanium alloy fan blades for the Rolls-Royce RB 211-535 E4 engine. These efficient wide-chord blades are made from titanium honeycomb sandwiched between two pre-shaped IMI 318 skins. (Courtesy Rolls-Royce Limited)

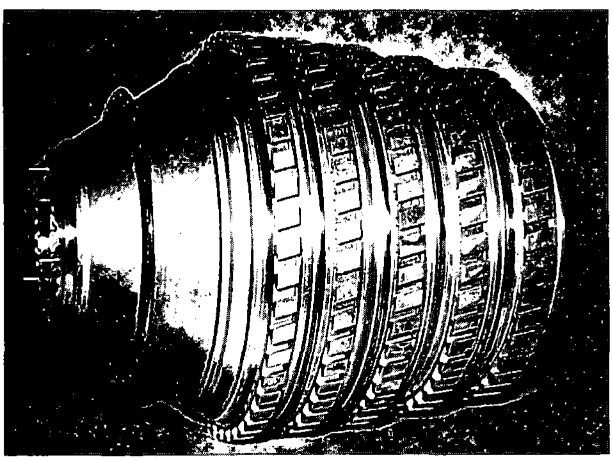

Fig. 2: All-welded HP compressor drum in IMI 685 alloy for Rolls-Royce/Turbomeca Adour engine. (Courtesy Rolls-Royce Limited)

engine).

In the USA, the Ti-6242 alloy is used for high pressure compressor discs in large fan engines. In Europe the most widely used, near alpha alloy is IMI 685, for discs and blades in the RB 211, RB 199, Rolls-Royce/Turbomeca Adour and SNECMA M53 engines. The weldability of this alloy is exploited in the construction of welded drum assemblies, offering weight savings over bolted structures (Fig. 2). The maximum operating temperature for titanium has been raised by further development of near alpha alloys, for example IMI 829 (Ti-5.5Al-3.5Zr-3Sn-1Nb-0.25Mo-0.3Si) and more recently IMI 834. The variation of properties with temperature of alpha-beta and near alpha alloys used in gas turbine engines is compared in Fig. 3; creep strength in Fig. 4; and low cycle fatigue properties in Fig. 5. IMI 829 is capable of withstanding 600^{o}C and has been selected for the final three stages of the -535 E4 HP compressor, resulting in a weight saving of some 120 lb over an alternative design in a nickel alloy.

Work on the development of high temperature creep resistant alloys in recent years has probably been greatest in the UK. It led to IMI 829 as mentioned above, and also more recently to IMI 834. Both materials are near-alpha alloys, IMI 829 involving beta heat treatment, and IMI 834 alpha-beta heat treatment. By a closer understanding of thermomechanical processing and its relation to alloying, conventional titanium alloys have been produced which are capable of operating up to 600^{o}C. The technology now permits the tailoring of alloys by thermomechanical processing and microstructure to achieve a particular combination of properties. For example, in IMI 834 practical heat treatments have been developed whereby a better combination of burst strength, fatigue and creep strength has been achieved.

It would appear that we have now reached a temperature, possibly in the range 600-650^{o}C, where long term surface stability will limit the performance of conventional alloys. Further significant advances may require a change in the direction of alloy development, or different methods of application.

It would seem that whilst alloy development has gone along this path in the UK, the direction of work in the US has tended to be more on the potential of titanium aluminides. The most favoured composition would seem to be Ti_3Al containing up to 20% niobium. There is no doubt that the aluminide family of materials has excellent resistance to oxidation. However, as found in other aluminide systems, high temperature strength and room temperature ductility usually need to be improved. As far as stressed uses in civil engines are concerned, the materials will presumably face a protracted period of validation.

Tight process control and quality assurance have always formed an integral part of the manufacture of titanium alloys for gas turbine applications. In recent years, titanium producers and forgers have been increasingly called upon by the aero-engine companies to supply components which must meet not only the usual mechanical property specifications, but also additional macro- and micro-structural requirements to ensure the highest consistency and reliability. Material for such components, referred to as disc or premium quality, is now specified for critical rotating parts such as compressor discs in current and future gas-turbine engines.

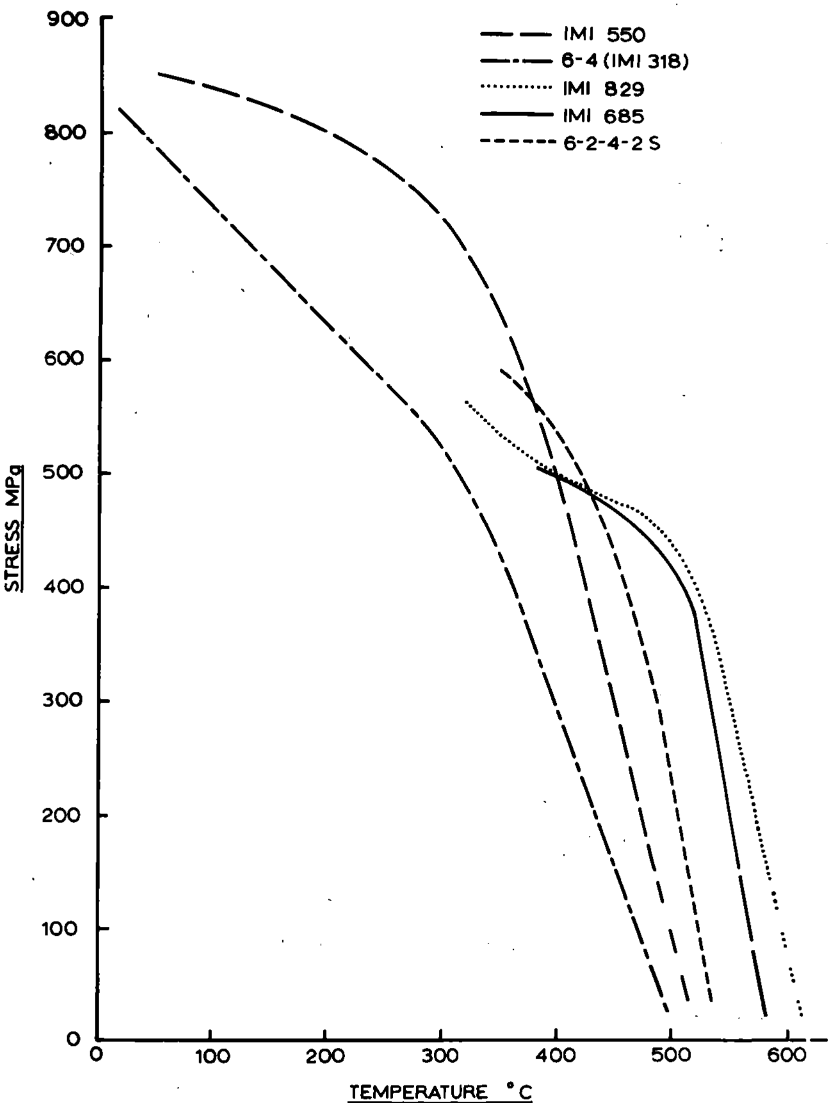

Fig. 3: Tensile strength of current titanium alloys.

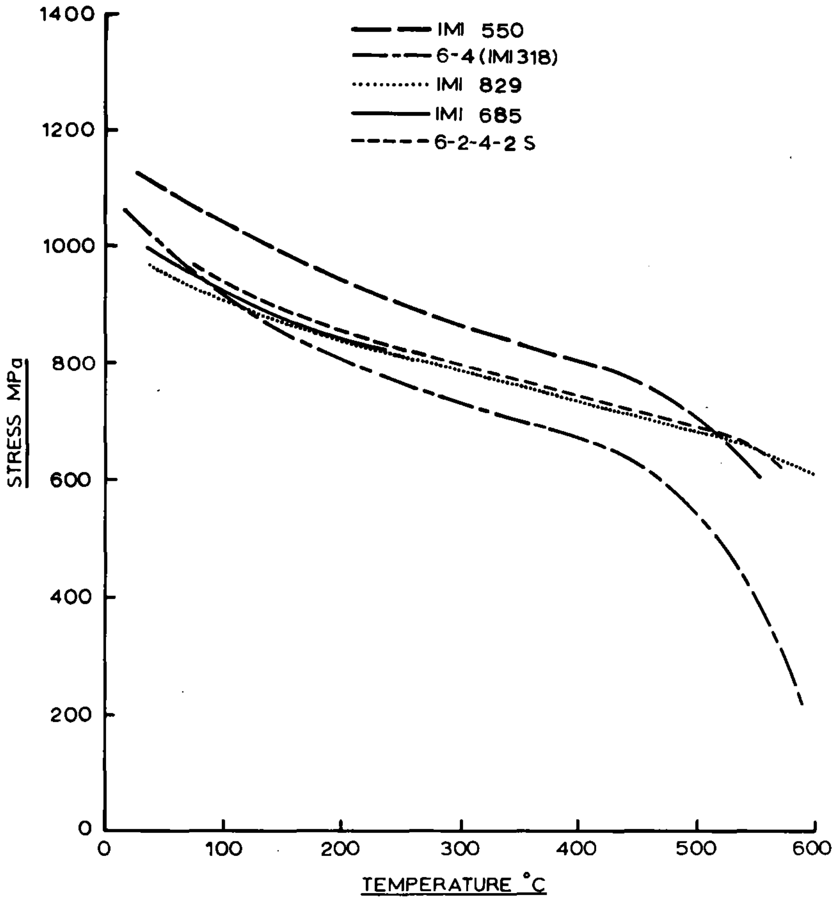

Fig. 4: Creep properties of current titanium alloys. Stress to produce 0.2% plastic strain in 100 hours.

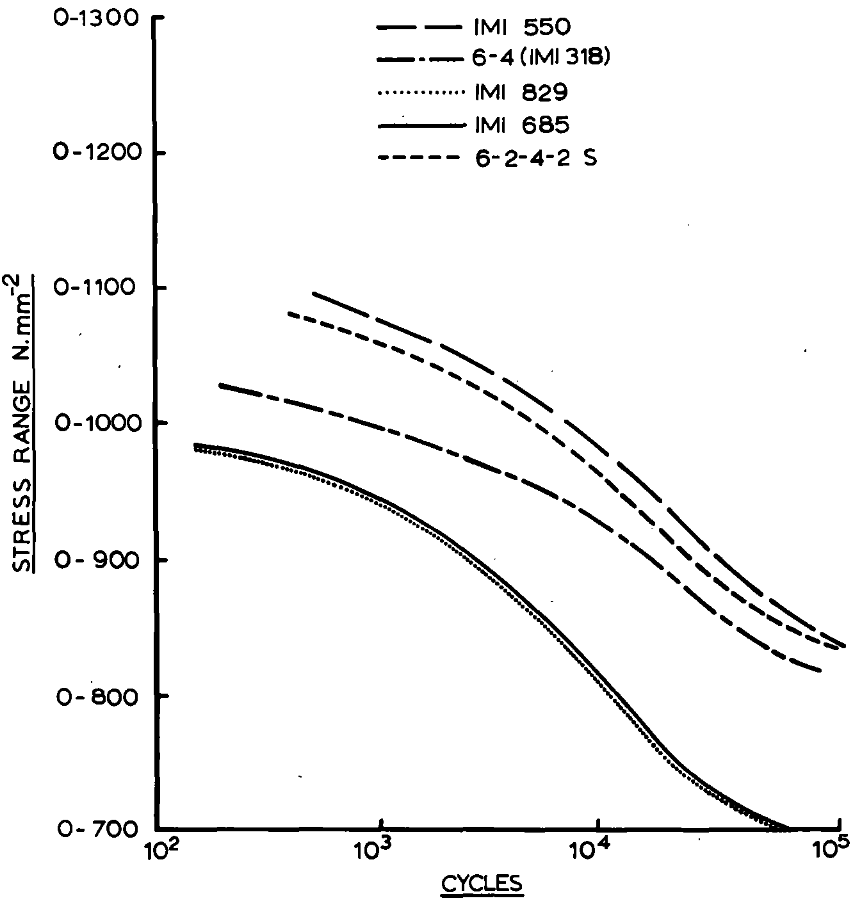

Fig. 5: Low cycle fatigue properties of current titanium alloys at room temperature.

Airframes

The use of titanium has grown to reach around 7% of civil aircraft structure weight and as much as 20-25% of the structure weight of modern military aircraft. The reasons for choosing titanium in preference to other structural metals are much the same as those for using the metal in aero-engines: with its low density and high strength of over 1200 MPa in the strongest alloys, it provides significant weight savings over alternative materials. Typical applications include bulkheads, de-icing and air-conditioning ducting in civil aircraft, and aircraft fairings, keels and fuselage panels in military aircraft. Commercially pure titanium tubing is used for air-conditioning and other low pressure applications, while 3Al-2.5V alloy tube is used for hydraulic fluid lines.

Complex high stress structures such as the wing box of the Panavia Tornado are made from welded and machined alloy plate (Fig. 6), this form of construction being made possible by the development of reliable electron beam welding techniques. The alloy chosen for the Tornado wing box was Ti-6Al-4V with some components of the stronger alpha-beta alloy Ti-6Al-6V--2Sn-0.5Cu-0.5Fe.

Flap and slat tracks in high strength titanium alloys such as IMI 550 (Ti-4Al-4Mo-2Sn-0.5Si) are found in both civil and military aircraft wings, for example European Airbus, British Aerospace 146, Tornado and Jaguar. Similar components in the USA are generally made from 6/4 or 6/6/2, but there is also interest in Ti-10V-2Fe-3Al for cost saving through forming closer to final dimensions. Where fracture mechanics considerations are important in design, the ELI grade of 6/4 is sometimes chosen.

In recent years, the technology of casting titanium alloys has progressed to the point where, especially after HIP-ing, castings are becoming more widely used by designers. Castings in Ti-6Al-4V are used in the Panavia Tornado, European Airbus, the joint UK/USA AV8B Harrier, Westland Lynx helicopter, and in space flight hardware.

Manufacturing techniques such as isothermal forging to near final dimensions, manufacturing of shapes from titanium alloy powders, and the HIP-ing of cast and powder parts, have been successfully developed. The discovery that fine grained alpha-beta alloys such as Ti-6Al-4V exhibit superplastic behaviour when deformed slowly at temperatures around 900^{o}C has led to production-scale processes for the manufacture of complex parts from thin sheet. The fact that in the same temperature range the titanium alloy will diffusion bond to itself has led to predictions that complex components could be made with a weight saving of as much as 30% over conventionally fabricated titanium alloy structures, and a corresponding cost saving. Fig. 7 shows a slat track jack can for the Airbus, made by superplastic forming.

Powder metallurgy products are not yet fully accepted aircraft parts, mediocre ductility, fatigue strength and fracture toughness being the main drawbacks. Current developments aim to improve these properties by forging or by hot isostatically compacting a PM preform. Pre-alloyed powder techniques offer the chance of fine structures in large parts, but are more expensive than conventional powder metallurgy, not only because of the cost of making the powder, but also because it is not easy with

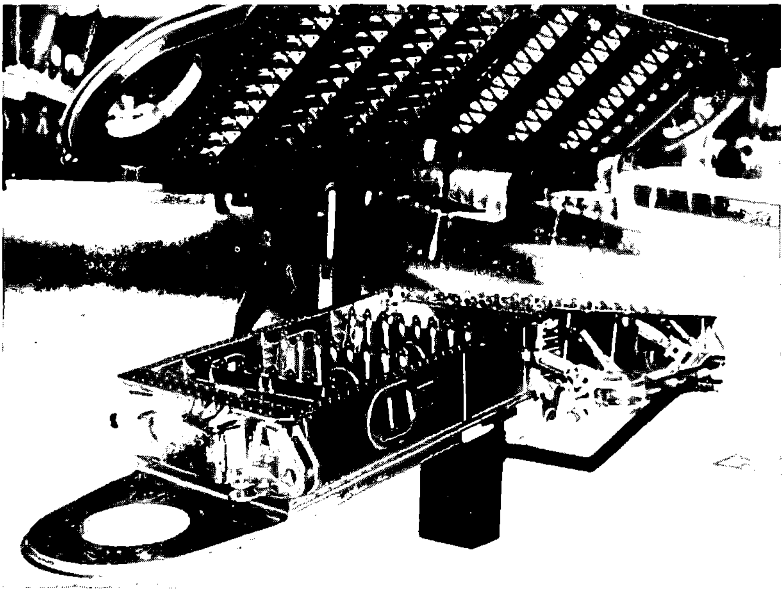

Fig. 6: Centre wing box of the Panavia Tornado, welded from 6/4 and 6/6/2 alloy.

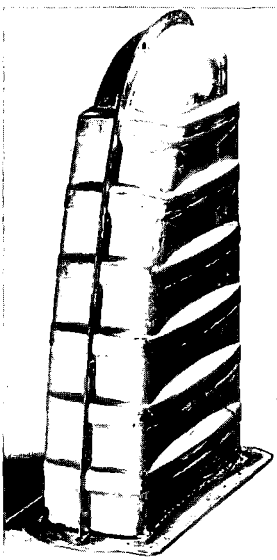

Fig. 7 : Slat track jack can for the A310 Airbus superplastically formed from 6/4 alloy. The can is approximately 500mm deep. (Courtesy British Aerospace plc)

conventional pressing and sintering techniques to cope with the comparatively coarse, strong powder. A number of different powder-making techniques are under development, with a variety of consolidation methods including hot pressing, hot isostatic pressing, or hot isostatic pressing and forging. Picking the technical and commercial winner is impossible, but there is a great incentive to produce a fine structure in a large part at close to final dimensions.

Competitive Materials in Aircraft Construction

Composites, special steels, aluminium alloys, nickel alloys and ceramics are all candidates in competition with titanium for selection in engine and airframe components. In spite of this however, the proportion of titanium has been maintained or increased in almost every area over the past few years. Significant growth in the proportion of composites used in aircraft structures has been accompanied by a slight increase in the use of titanium. For example, in successive versions of the Harrier/AV8 VTOL aircraft, the use of composites has increased to 26%, while at the same time use of titanium has risen from 7 to 9% as the need has grown for metal fasteners for the composite parts. Nickel alloys and ceramics are in competition for engine components operating at temperatures too high for current titanium alloys. When fully developed, ceramic components may change the temperature profile of the whole engine and alter the product mix, but the overall effect is unpredictable. In any event, a very considerable amount of testing and proving must be done before ceramics find any significant volume use in civil aircraft.

General Industrial Applications

It is encouraging to report that increasing applications are being found in general engineering, based on titanium's high strength to weight ratio. In high speed reciprocating or rotating machinery, titanium can ensure better performance either by allowing a higher speed to be attained, or by reducing the amount of energy required to drive the equipment. Typical applications include steam turbine blading, connecting rods, crank shafts, cam shafts and springs in high performance engines; suspension arms, torsion bars, springs, drive and transmission shafts in racing cars; and cycle and motor cycle components. Titanium ultracentrifuges used in biological research provide higher 'g-forces', thus enabling more rapid and effective separation of samples. Other established and potential uses based on good specific strength include packaging machinery, telephone relay mechanisms, and ultrasonic welding probes.

Coupled with its attractive mechanical properties, the outstanding corrosion resistance of titanium to sea water continues to increase its applications in marine engineering. For example, the use of Ti-6Al-4V for data logging equipment exploits high strength and the corrosion resistance both to sea water and to hydrogen sulphide. Low density is an added bonus in this application but, in the case of fans in tanker purge systems, it is a vital property as the fans become larger. Titanium alloys are also being used in deep diving vessels for structures, pipework and the pressure spheres themselves. It is unrivalled for depths greater than 2000 metres, but also may have advantages over conventional materials in shallower waters.

While the material has not yet found significant application in shipbuilding, its non-magnetic properties are an advantage for a variety of components in minesweepers. Other uses include hydrofoil struts, foils and engine components; propeller shafts; sea water trunking for fire fighting vessels; mast top radar components; cathodic protection anodes and yacht fittings. The most dramatic use of titanium for shipbuilding is in the form of titanium-hulled submarines built in the USSR.

Titanium and Heat Exchange

Titanium is an ideal material for heat exchangers, whether plate type or tube-in-shell, and thin-walled titanium tubing is now an established material for main steam turbine condensers in both nuclear or fossil fired power stations. In the UK alone, IMI titanium tube installations exceed 26,000 MW, and the total for the non-Communist world is well over 100,000 MW. As well as main condensers, titanium is also extensively employed in the auxiliary cooling circuits of modern power plant, for such applications as demineralised water coolers; dump condensers; pond coolers; turbine and other lubricating oil coolers; feed and air pump coolers; and generator transformer coolers.

In the offshore oil industry, the excellent corrosion resistance of titanium to sea-water and also to sulphide-bearing crudes and gases is exploited in gas/oil product cooling. Onshore refiners have of course used titanium-tubed heat exchangers for many years, particularly where the poor quality of available cooling water causes corrosion of alternative materials.

MSF desalination plants provide large markets for titanium; plants have been installed in Japan, Algeria, Peru and Indonesia, but these are small compared with those in Saudi Arabia, the largest being at Al-Jobail which contains over 2500 tonnes of tube. Total weight of titanium tube used worldwide today for desalination must be over 6000 tonnes; the use of tubes with wall thicknesses of 0.5mm or less is being pioneered in Japan, giving significant cost savings.

Another possible major use of titanium tubing would be the ocean thermal energy scheme (OTEC), which makes use of temperature gradients in the sea to generate energy. Should titanium eventually be selected as the heat exchanger material here - it has performed excellently in tests to date - very large quantities of tube would be required.

Titanium's good corrosion resistance in organic chemicals has led to applications involving benzoic acid, acetic acid, malic acid, ethylene amines, and terephthalic acid. Some of these represent large scale uses involving pipework, heat exchangers, pumps, valves and vessels of solid, loose lined or explosion clad construction.

Titanium and Surgical Implants

With almost 20 years of use in surgery, titanium has demonstrated excellent compatibility in the body. No instance of adverse tissue reaction to titanium has been recorded, and a considerable amount of laboratory work has proved its resistance to simulated body environments, under both stress and fatigue and in crevice conditions.

The mechanical properties of the commercially pure grades and the alloys of titanium offer a wide choice to the medical engineer. Soft commercially pure titanium is used for cranial surgery where formability is essential. The hard commercially pure grades are used for bone plates, screws and some joint prostheses. The medium strength alloys such as Ti-6Al-4V have grown rapidly and are now the principal titanium alloys for the manufacture of such items as bone screws and hip and knee joints.

The relatively low modulus of titanium compared with stainless steel has led to some criticism that there is lowering of the rigidity of bone plates. However, in most cases this problem can be overcome by increasing the cross-section of the plate to achieve a similar rigidity. In the total replacement of hip joints, the low modulus in fact appears to be an advantage, in that the rigidity of a titanium implant is nearer to that of the bone it replaces than would be the alternative materials. This results in less bone resorption and the implant remains securely fixed.

The advantages of titanium in its biocompatibility, low modulus, fabricability, and ready availability in a wide range of forms have led to other uses in surgery over the past few years. In dentistry for example, titanium denture pins are used regularly in situations where large scale reconstruction of teeth is necessary. Titanium alloys are also being actively considered as root canal posts to which crowns are attached. In both of these examples, the good compatibility of titanium with body fluids is the most important factor.

Titanium and Electrochemistry

Because of its well known 'valve metal' properties in electrolytes, the use of titanium as anode and cathode devices has continued to grow, but at a slower rate than before. These items have long lives and some markets are becoming saturated.

The main electrotechnology use for titanium is of course as DSA anodes in the production of chlorine. It is also used as heat exchangers for brine preheating and for chlorine cooling, in the latter application replacing glass exchangers with many times the surface area. Vacuum dechlorination of spent brine requires titanium coils and titanium liquid ring pumps, while butterfly valves, demisters and precipitators handle the wet gas after it has been produced.

Titanium anodes coated with platinum are also used for cathodic protection of steel structures in saline waters. A further use which is growing is as anodes for manganese dioxide production. Again, titanium is more cost-effective than graphite and provides a product of improved quality, suitable for manufacture of high performance dry cells.

The oxide film on titanium cathodes acts as a parting agent, enabling electro-deposits to be removed easily, as well as providing a surface on which the deposit nucleates well. The major use is for the production of copper starter sheets for electrolytic refining, and titanium has now almost completely replaced the traditional copper starter sheet blank, which needed oiling every cycle and suffered liquor-level corrosion. Productivity was much improved by the change to titanium, as well as a significant increase in the percentage of good starter sheets. Titanium is also used in the electrolytic production of gold and manganese. Conditions for manganese production are particularly harsh; titanium cathodes last several years despite constant use in hot sulphuric acid-based liquors, with copious electrolytic hydrogen evolution and repeated battering by the hammers used to remove the brittle manganese product.

Other Uses

In addition to the outlets reviewed above, titanium continues to find an increasing range of uses. The most interesting is perhaps in the form of niobium-titanium or niobium-tin superconductors. Although the growth of applications has been rather disappointing - nuclear fusion for example is still only at the experimental stage - there has been some increase. As is often the case in hi-technology, the most exciting application was not even foreseen at the time of introducing superconductors. This is the use of NMR in whole-body imaging medical diagnosis, which has grown dramatically in the last few years.

Small quantities of titanium and its alloys have been used in a bewildering range of products, and it is becoming an impossible task to list all of them. A noteworthy trend is the wider uses in consumer products such as golf clubs, costume jewellery, spectacle frames etc.

General Comments

Titanium is a metal with an exciting and impressive portfolio of properties. It is available in all mill product forms, produced to the highest standards of quality. Since the last International Conference production capability has been increased throughout the whole Industry, to meet the demand that was projected in 1980 from the Aerospace industry. Because these forecasts have failed so badly to come up to expectations, this capacity is currently very seriously under-utilised. This is an economic handicap, but at least it is clear that there is no shortage of capacity, either of raw metal or of mill products, to meet any reasonably foreseeable demand.

The driving force behind most of the developments in titanium has been the aircraft gas turbine, and our success in meeting these challenges has been very largely due to the remarkable co-operation between the producing and the using industry. With fuel now representing over 50% of the direct operating cost of civil aircraft, which will lead to ever higher cycle temperatures and pressures, advanced materials will continue to play a key role in future engine designs. There is no doubt that the titanium industry will continue to rise to this challenge as it has done successfully in the past, and the aerospace market will continue as our most important business sector.

However, in following this path we must continue to safeguard the 'balance' of our approach and the deployment of our technological and financial resources. For example, in working on PM components, say by RSA techniques, we must not forget about the cost efficiency of the route. The cost advantages of the finished product have got to be measured against the cost of producing the raw material; the cost of making the product; the cost of inspection; the cost of rejection - all of which have got to be borne by, say, a better net-shape-yield. If the advantages are in, say, product properties, then the effort must be measured against the size of the market.

In short, we must not be over-attracted by the 'Novelty' (or even Difficulty!) of a particular process or a product. Certainly, we must be aware of changes and improvements in the technology, whether in our producing industry or by our customers. For its own sake however, Novelty is a danger.

In this respect, we might usefully contrast the quite remarkable 'track-record' of titanium in establishing and penetrating non-aerospace, Industrial markets, which now account for a large proportion of our sales: PM coated dimensionally stable anodes; metal refining; applications in 'offshore' oil; heat exchangers of all types; desalination, and so on. It would be foolish to expect the same pace of development to carry on into the future. The picture has been clouded by the general recession in world trade but even had this not happened, it is unlikely that we would have seen the same rate of new product development as in, say, the 1960's and 1970's. To this extent therefore we are on something of a plateau, and need some additional stimulus to recover the old rate of development. Better design of products to take maximum advantage of the properties of titanium could be one stimulus; reduction in price could be another. We will need both to build up new sales volume, inside and outside our traditional markets.

There are few, if any, metals or materials which can claim such a wide range of properties and applications as titanium. It has made certain markets its own by providing demonstrable value for money, and demand in these markets will therefore rise and fall with their prosperity. We should note however that with improved efficiencies, engineering product designs and applications of titanium, the increase in demand will not necessarily be pro rata. New inventions will become more difficult, as we have seen in trying to extend the use of titanium anodes into the electro-winning of metals rather than chlorine. The work will however go on, as evidenced by the many papers to this Conference. Some of the possible directions are highlighted below.

It is reasonable to say that if the Aerospace industry had not deliberately designed around the known properties of titanium and set the producers targets for alloy properties, the application of titanium in aircraft would have been much slower and less extensive. Unfortunately this is not always the case in Industrial applications. In steam condensing for example, where there is more than ample corrosion resistance to last the life of the condenser, we are still in some ways simply using titanium in designs which were drawn up for other materials. Certainly we use thinner wall tubes, but they could be even thinner and often they are usually still plain tubes. The use of extended surface tubing to improve heat transfer has been very slow in development, and yet one feels that this is where the real benefits of titanium should be made to pay.

By doing this, and hopefully some progress is being made, we shall increase the benefits available to our customers in improved performance or lower capital cost and, hopefully, increase the level of business for ourselves. Calculations of the benefits of roped tubes, for example, for power station or ship-board condensers, or for use in OTEC evaporators, indicate a saving of 15% in capital cost compared with plain tubes. This ought to be just a beginning.

We sometimes boast about the long life which is provided by titanium, but the life might in fact be too long if it exceeds, for example, the obsolescence life of the equipment. And this in itself might cause the cost of the titanium to be too high for the engineer to use. We might break out of this vicious circle if we fully exploited the properties of titanium.

Another aspect which has been slow in development is the exploitation of the mechanical properties of titanium alloys in industrial applications. These do not have the glamour of aircraft nor represent such a price for saving energy, but energy saving will always be a selling point, even currently when energy is not quite so expensive as it might have been. The old application in steam turbine blading will grow, but what I have in mind is any sort of moving machinery, especially that which starts and stops frequently. The use of titanium alloys should reduce the energy necessary to bring the machinery up to speed, as well as to stop it; again to provide benefits to our customers in improved performance or lower capital cost.

This sort of application engineering should be helped by industry-wide promotion such as envisaged in the recently formed US Titanium Development Association, and of course by the similar Association in Japan.

A major handicap holding back such development is the first cost of the material. Much is heard these days of 'the cost of ownership', but to an engineering designer who is having to reduce his initial capital investment, it is a difficult task to try and 'sell' him a reduced maintenance charge, or a high disposal value of the obsolete plant; important though these may be. The most powerful factor in a cost of ownership presentation is often a lower cost of purchase!

There is however often a lot of misconception with designers about even the first cost of titanium. The facts are that titanium is less costly than many competitive, better-known 'premium alloys' such as Hastelloy, Monel and so on. Again, correcting this misconception is an important task for our Industry.

Nonetheless, we have here a paradox, which is that titanium provides such splendid corrosion resistance <u>because</u> it is difficult and therefore costly to extract. Except for the noble metals such as gold, the one property usually goes with the other. However, unless we can reduce the cost of titanium consistently, and this includes the energy cost of titanium at the raw metal stage, then the production and development engineers will always have an uphill task in expanding markets: despite successes in making or melting larger unit weights, and processing on modern efficient plant, or even redesigning to make better use of the properties of titanium. This will remain a continuing challenge.

Conclusions

At a time when we are just emerging from recession, it would be very optimistic to project a worldwide demand of 200,000 tonnes p.a., even by the year 2000, as was forecast at the last International Conference in Kyoto. It would also take a very bold forecaster to predict so far forward, when our history shows periodic cyclical growth and shrink rates of as much as 30%; even against an average growth trend of 8-10% p.a. over many years. Suffice to say that the fundamental properties of titanium will still sustain healthy growth in the future, as in the past.

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