F.H. Froes
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ADVANCES IN TITANIUM TECHNOLOGY

Thank you for the kind introduction. My name is Sam Froes and I am from the AFWAL materials laboratory in Dayton, Ohio. Today I'm going to try to give you an overview of some of the most recent developments which have occurred particularly in the aerospace industry in Titanium technology.
I would like to talk about some of the advantages and disadvantages of Titanium, although I'm pleased to hear that cost is no longer a consideration, so I'll be able to eliminate almost half of my presentation. Areas which I'm going to cover, some of them in some detail, some in less detail, are reported in fig. 1. I might say for those of you in the audience who have not seen it that there is a publication put out by the Titanium Development Association, which perhaps, you can see here, which is called "Titanium Technology" which I edited with two other people. I believe there is a copy of this book in the hallway before you come into the auditorium. I think it's a good book, but of course I'm biased since I'm the editor and also the author of a number of articles in that book. If you want a copy, it can be ordered from the Titanium Development Association in Dayton Ohio (*).

Titanium does look very attractive in comparison with Steel. It also looks attractive compared with Aluminum and Magnesium when we look at the melting points, as Titanium melts at a much higher temperature (fig. 2). So Titanium has the advantage compared with Steel of low density, and compared with Magnesium and Aluminum of a high melting point, therefore a higher temperature at which it can be used. Also the crustal

(*) "Titanium Technology" edited by F. Froes and D. Eylon – TDA abundance, that is the amount of Titanium which occurs in the surface of the earth, is quite high, which is one of the factors relating to the cost, but of course not the only one, since Titanium and Oxygen are very attracted to each other and it is difficult generally to get Titanium from its ore.

If we look at the effect of density on the total weight of a structure (fig. 3), a very important factor in the aerospace industry, then density directly gives you a reduction in weight as compared with strength and modulus which do not give this direct reduction in weight, so density is very important.

If we look at where Titanium is compared with some other materials (fig.4), both metallic materials and non-metallic, we can see that currently alloys like Aluminum are only useful up to perhaps 300 degrees Farenheit (300F) (like the 2219 alloy used on the leading edge of the Concorde wings), but there are developments there, rapid solidification in particular, which now allows to take Aluminum alloys to temperatures perhaps as high as 650 degrees Farenheit, lower density Aluminum alloys like the Aluminum - Lithium alloys which can be either Ingot Metallurgy alloys or again rapidly solidified alloys. There are also advances in the non-metals, both in the Thermoset resins and the Thermoplastic resins.

In advanced systems, in the United States and in other countries, like advanced fighters, (the ATF advanced tactical fighter) there will be a considerable percentage of these non-metals in use.
However Titanium is also showing advances which I will talk about today, both monolithic Titanium and Titanium Composites where we can now see the potential with using these materials beyond the conventional thousand degrees Farenheit, perhaps as high as thirteen degrees Farenheit and even higher. Even in composite airplanes we will see a lot of Titanium in a relative sense, because Titanium is very compatible with the composites:

it has a good coefficient of thermal expansion (CTE), it also can transmit loads very well from the composites to other locations in the system, and the other advantage of Titanium, compared with Aluminum, is that there is no Galvanic corrosion problem between the composites and Titanium (fig. 4bis). So even in an all-composites, a socalled all-composite airplane, we will still see perhaps as much as 20% Titanium, that will be more Titanium than for example in the F 16 where there is only 2 or 3%.

Looking beyond the airplanes, the United States Airforce and other countries throughout the world, including the Soviet Union, are looking to moving to space as quickly as possible. Here we are talking about such systems which are advanced beyond the Shuttle; systems which are able to fly into orbit, perform a mission, come back to earth, and then return on demand, that is immediately, into orbit. This would be a system like the National Aerospace Plane (NASP). An artist rendition of what that airplane might look like is shown in fig. 5 a and b. When my son saw this, he said: "That looks like a real fake to me, that looks like somebody made it out of a piece of paper and just stuck it up towards some kind of background". So he didn't like that one... he did like this one. This is what that system will really look like. It will be white heart on the nose and will be red heart along the rest of the surface as indicated in the picture. This is an artist rendition, of course, but those colours do correspond to the real temperatures on that vehicle. So the challenge is very great. We need a low density material and we also, at the same time, need something capable of high temperatures. So Titanium is obviously one of the preferred choices for this system.

I am allowed to do a small amount of advertising in this presentation, beyond talking about my book of course. Federal Express who always guaranteed to deliver parcels on time asked me to show their version of the NASP (fig. 6). Here it is and they guaranteed that they would deliver a package from Torino to Tokyo now in twelve hours and it will only cost you $2000 per kilo to have your parcel delivered... if you are lucky.

I am unable to talk about many more details of the National Aerospace Plane because there is a lot of secrecy attached to it and obviously it is a vehicle which not only can be a commercial vehicle, a socalled Orient Express, but also can of course perform a military mission. I was very surprised again to see one of my son’s publications called "Popular Science" (fig. 7) which in the May edition of the last year contained many more details on the National Aerospace Plane than I am allowed to talk about. So I will have to complete my presentation on the National Aerospace Plane at this point but I would suggest that if you want many more details, as I said, than I am allowed to talk about, look in one of the magazines: "Popular Science".

In addition to the use of Titanium in airframes, there is also a lot of Titanium in an engine. Fig. 8 shows the advanced F 100 engine: it shows not the weight of Titanium which actually flies in the engine, but the amount of Titanium which is going into the engine as import weight. If we could replace the Nickel base materials with Titanium we could reduce the weight, and, as in the airframe, even more so than in the airframe, weight is very important in the engine.
For every pound in weight that you can save in the engine over the lifetime of the airplane it is worth about a thousand dollars. For every pound in weight saved in the engine, because of balancing effects, that is location of the centre of gravity of the aeroplane, you can save another five pounds in the airframe. So for one pound in weight saving in the engine, there is a total of six pounds weight saving, times perhaps a thousand vehicles in a fleet, and times however many pounds you can save. Very big numbers if you can replace Nickel with Titanium.

As I said, I am glad to hear that we no longer have a problem with the cost of Titanium because increased use of Titanium does provide many advantages and you can see some of those advantages shown here, and I no longer have to turn this over and show that the cost reduces the amount of Titanium that is used.

Fig. 9 reports data three years old, but they still demonstrate the fact that as we go from the pure Titanium-Oxide from rutile, particularly to melt products, because of the cost of Titanium production, the cost of Titanium forging, fabrication and the high cost of Titanium machining we get to a component having very high cost. So there is always the desire, by the people who are in charge of the cost of an aeroplane, to try to reduce the amount of Titanium whereas the people who design the aeroplane like to have as much Titanium as possible. Picture 10 shows the comparison between the amounts of Titanium used in early designs of three systems: a bomber, a fighter and a cargo aircraft in comparison with the final concepts. Where the performance of the vehicle is very important, it was impossible to reduce by any great amount, the amount of Titanium in the aircraft. In the less demanding application, that is in the cargo aircraft, then the amount was reduced by a factor of almost ten.

But still, the amount of Titanium being used, both in military applications, increases, although there are some questions now in the United States, for example what will happen beyond the end of the B 1 program, but as I said for the advanced tactical fighter it is likely that there will be perhaps as much as 20% Titanium.
The price of Titanium is coming down and fig. 11 shows the price per pound of Titanium over the last few years.

Moving on now to some of the technological areas, as I said, some of them I will discuss in detail, others I will just touch upon briefly.

The company who is organizing the meeting today is one of the leaders in terms of innovative processes for producing Titanium. Other details on that can be found in the book that I mentioned earlier. One process which we, at the United States Airforce, have been interested in, is the Albany-Titanium process (fig. 12).

It is a process in which fluorination is followed by a reduction in a Zinc-bath, by Aluminum, and finally a distillation step to produce a Titanium powder, or sponge, or even an alloy powder which does not contain the remnant Sodium or Magnesium salts that the Kroll or Hunter process do. It is still an experimental process, and only small amounts of material have been produced at this point.

Melting of Titanium is an area where a lot of work has been done in the last few years particularly because of the concern with defects, in particular the socalled Type-1 defect which is an alpha-stabilized defect (particularly stabilization with the elements Oxygen and Nitrogen) (fig. 13). Because of this, there has been a lot of attention paid to other techniques beyond the consumable electro-techniques including those shown in fig. 14 particularly Electron-beam and plasma-techniques although it is recognized that with either one of those techniques the melting of Titanium will be more expensive than with the Vacuum Arc Remelting technique.
There have been other techniques investigated such as Inductoslag sligh techniques developed at the Bureau of Mines in Albany, Oregon, and more recently commercialized by the Duriron Company in Dayton, Ohio. This technique probably being more applicable to small castings rather than the production of Ingots.

I will not cover welding or corrosion today but as I said those are also covered in the book that I mentioned earlier and which is available from the Titanium Development Association.

I would like to mention, however, the Beta-Titanium alloys, that is alloys which are sufficiently alloyed with certain additions to stabilize a body-centered cubic face rather than the hexagonal closed pact face.
At room temperature one major advantage of the body-centered cubic face is that because it is a cubic system there are many more slip systems which can be activated and therefore a lot more ductility in the material than in the conventional hexagonal closed pact material (Fig. 15).
Some of the alloys which have been developed over the last few years are shown in fig. 16 starting with the Beta 1 alloy, or 13-11-3, which was used extensively on the very high-flying and fast surveillance airplane, the SR 71.
There have been other alloys developed in this class however in more recent years which are much easier to work with than the 13-11-3 alloy; particularly the two alloys shown at the bottom, that is the 10-2-3 alloy, which is a forgeable alloy, or used mainly in forging applications, and the 15-3 alloy which seems to be more applicable to sheet applications, although this also would be relatively easy to forge.

I will go back to the high strength Beta-alloys a little later when I talk about rapid solidification, but now on the higher temperature alloys where the major use to date has been in the gas turbine engine (fig. 17).

What we are now trying to do is to develop alloys which take a jump foreward in terms of the types of alloying condition, particularly techniques such as rapid solidification where we can get dispersion strenghtened alloys, similar to some of the dispersion strenghtened Nickel-based material, and dispersion strenghtened Aluminum materials which I referred to earlier.

Also developments are coming in terms of being able to use some materials which in the past were considered too brittle to use, particularly things like the Titanium-Aluminides, perhaps

again in conjunction with rapid solidification and dispersion strenghtening.
Some of the advances which have come in the high temperature use are shown in fig. 18, where the advanced Rolls Royce engine, the energy efficent engine RB 211/535 is reported the areas shaded show the areas in which the advanced alloy IMI 829 is used. It is in the second, third and four stages for the blades and four, five and six for the discs. This engine is being used, I believe, on some of the 757s.
We're also seeing advances in casting and fig. 19 shows some of the very complex shapes produced, used in the casting techniques, these, as you can tell from the top part of the viewgraph are components which were made by the Precision Castparts Co. in Portland, Oregon. Not only can aerospace parts be produced, but also parts such as the prosthesis shown in fig. 20. The advantage of Titanium, just as in the aerospace industry, is the light weight and the corrosion resistance. If you can use Titanium in this part rather than the conventional steel, the reduced amount of weight in the knee is sufficient to avoid the operation which is required on your ankle because of the increased weight of Steel, about five years after putting the material into the knee; so a big advantage, an advantage in terms of being able to do the operation to younger people is reached.
Not only are we in the free world, in the Western world, very interested in Titanium castings, but also of course in the Soviet Union there is a very advanced Titanium technology. They for example have a statue of Jurij Gagarin which is in Moscow and that statue is made out of a cast Titanium (fig. 21).

We've done a lot of work in trying to improve the mechanical properties of castings in addition to the shape-making capabilities which I showed you a little bit earlier. Fig. 22 shows, in summary form, some of the average fatigue curves for 6-4 alloy cast material both compared with base line material and various heat treatments, some of which use hydrogen as a tempering alloying element, the socalled thermochemical processing.

I would now like to turn to Powder Metallurgy and here I would like to briefly discuss, but only briefly, the blended elemental approach which is a little more conventional, spend a little more time on prealloyd and then some time on the rapid solidification approach.

Blended elemental (fig. 23) is an approach in which normally, as I mentioned earlier, we have chlorides present and these chlorides generally have led to a degradation in the mechanical properties, particularly initiation related properties such as fatigue. The problem there is that, as you can see from the photo micrographs in fig. 24, particularly on the left, the salt which is present also has voids associated with it which gives it a degregationing fatigue. However, again, using innovative treatments, and this is work again from my laboratory, we've been able to improve the mechanical properties.

Next picture (25) shows the effect of baseline material and beyond that the BUS (Broken Up Structure) treatment which is a long-time Alpha-Beta heat treatment in which the continous layers of Alpha Beta are broken up, so to a broken-up structure, a Bus structure and also the use of Hydrogen as a temporary alloying element, that is the HDH process (Hydride de-hydride process) again refining the microstructure and giving an improvement in the mechanical properties.

The current status of blended elemental approach is that many parts have been made for non-critical, non-fatigue related parts: for advanced to occur in this technique, particularly for using critical parts, we must make use of salt-free sponge, unless it is possible using techniques such as Hydride de-Hydride; the levels of salt which are required are less than a houndred parts per million.

In the field of pre-alloying, we have the alloying elements present in the material already; the powder is produced by a number of techniques, as atomization, which can include the

PREP-process (Plasma Rotating Electrode Process). Here the mechanical properties are very close, or even exceed those of conventional material, fatigue crack growth rate, which is shown in fig. 26, where the fatigue crack growth rate is the same as Ingot material with the same type of microstructure.

We do have concerns always with powder and that is, if there are contaminants present, then the mechanical properties, particularly initiation related properties, will be degraded. If we however eliminate all of those contaminant particles, then the Powder metallurgy material has properties which are as good as, or perhaps slightly better, than the convention material. By modifying the microstructure, as I've already described for cast material and blended elemental material, we can again improve the mechanical properties. Moreover it is possible to make very complicated shapes using the Ceramic mold process developed by Crucible Steel.

It is always a big question what will happen when you produce a part using a new technique like the powder technique: will it be accepted? It is interesting that for example, for a certain helicopter part produced by MBB in Munich, that when they were able to produce the powder part with the cost reduction of 40%, they went to the forging company and said: "we no longer want your forged part" and the forging company said: "That is amazing! Yesterday we had a major breakthrough and we're now able to produce that part with a cost reduction of 50%". So they did not achieve their objective of using the powder part, but they did get a big cost reduction.

Rapid solidification; here we are cooling the material very quickly from the liquid state to the solid state and you could define this in terms of a cooling rate; but more importantly I think it is to realize that, by using this technique, you are able to do things with the microstructure and the phases which are present, which are not possible by conventional techniques (fig. 27). I do not have time to go over all of the various attributes of rapid solidification, but as I said some of them have the capability close to net shapes and also improvements in the microstructure.

We have used the Titanium-6 Aluminum-4 Vanadium alloy for many years and stretched its capabilities to a maximum. In the United States it is called the "work horse alloy" (fig. 28) and that is the reason for showing the horse along with the name of the alloy.
What we are trying to do in Titanium, with rapid solidification, is improve the properties by these kinds of levels. Fig. 29 shows some of the advantages we're looking for, using rapid solidification. We would like to be able to improve the temperature capability of Titanium by as much as 300 degrees Farenheit. This would be in conventional, terminal type of Titanium alloys, alloys beyond the alloy 829 and 834 where we disperse and strenghten the alloys using additions such as rare earth oxides, rare earth sulphides or also the metalloyds Carbon and Boron and Silicon perhaps.

I've talked about the strenght of Titanium alloys; using the rapid solidification approach, we're able to produce some alloys which are not possible using conventional melting techniques, because of the very high amount of segregation which occurs with the conventional processing. It would also be nice to reduce the density of Titanium alloys as I demonstrated very early on today, density like no other mechanical property reduces the weight of a component. We get a direct reduction in the weight when we reduce the density and if we keep everything else the same. So density is a very big attraction. I've shown in fig. 30 a density reduction of 40% which would take Titanium down to the density of Aluminum. That would be a very attractive Titanium alloy. I see one or two people in the audience shaking their heads thinking that that is impossible. I will show you at least, the alloy which is capable of demonstrating those characteristics. The making of that alloys is however a challenge.
There have been some advances in the production of Titanium powder and next picture (31) shows a process which has been developed under United States Airforce's funding, at the

Crucible Steel Company in Pittsburg, Pennsylvania in which they are gas atomizing Titanium. This is a challenge, because Titanium, as I think most people in the audience today know, is a very reactive material in the liquid state. However, using material such as Tantalum and Tungsten, they are able to produce, at least at this point, experimental amounts of gas atomized material, perhaps a kilogram or two kilograms. They are hoping to scale that up very soon to amounts about ten times higher than that. Gas atomization is a much less expensive process than for example the PREP process (the Plasma Rotating Electrode Process) in which a precision ground electrode must be produced and then using that electrode, powder is produced. The number that we heared from Peter Roberts of Nuclear Metals at the Aerospace Conference which was held in Luzern, Switzerland earlier this week, was that even starting from the precision ground bar, the cost of the powder would be another fifteen dollars per pound beyond the import weight.

Using the rapid solidification technique, we are able, as I have already mentioned, to get rare earth dispersoids into the Titanium alloys and fig. 32 shows thin foil electromicrographs of two such types of dispersoids. One, an Erbia, that is Erbium Oxide dispertion, second, Cerium/Sulphide and as you can see the particles are stalled very small even after a relatively high temperature exposure: 1600 degrees Farenheit for about two to four hours.
What we are able to do with these alloys is to get improved creep-resistence, and next picture (33) shows the creep-performance at 1200 degrees Farenheit under a stress of 20 KSI; it is plotted as percentage creep against time in comparison with the beta treated 6242 S alloy, which is the highest temperature Titanium alloy used in the United States. You can see that the amount of creep which occurs in any certain amount of time is less in these dispertion strenghtened alloys than it is in the conventional alloy. So it offers the potential for using

Titanium to higher temperatures in applications such as a jet engine. If we can develope a 1300 Farenheit Titanium alloy using these dispertion strenghtening techniques, then it is possible in advanced engines such as the AFE, (Advanced Fighter Engine) which would be the propulsion system for the ATF (Advanced Tactible Fighter) to reduce the weight considerably by perhaps as much as three houndred pounds.

I talked about the Inter-metallics. Picture 34 shows the phase diagram for Titanium with increased amounts of Aluminum showing the two intermetallics that are of most interest to us. The Ti_3Al or Alpha 2 (α_2 and the TiAl (..) or Gamma intermetallic. The Ti_3Al or Alpha 2 behaves like a metal, we can do alloying, we can add things like Niobium to that to produce greater ductility. A much more of a challenge, however, is the Gamma alloy which doesn't seem to know whether it is a metal or perhaps behaves more like a ceramic material. So there the challenge is much greater. But we have been able to make advances again using things like rapid solidification; fig 35 shows melt spun (which is a ribbon of molten metal which is solidified on a wheel). Ti_3Al with 0.6 atomic percent Erbium, allowing a fine dispersion of second phase particles, dispersion which will give us improved creep performance even after a very high temperature hipping operation, that is 850°C.

Turning now to high strenght alloys there have been advances in the use of high strenght alloys, particularly on the systems like the 757 shown in picture 36. There were plans to try to get the 1023 alloy into the landing gear beam, (fig. 37) however at that time, it was the time about around 1980/81 where there was a great shortage of Titanium, so unfortunately that alloy was not used in that application. But the landing gear is a very attractive application for high strenght Titanium alloys. Fig. 38 shows the percentage of the total weight which is occupied by the landing gear in various advanced systems in the United States. You can see that the average percentage of the total weight of the landing gear compared with the total weight of the aircraft is about 14%. If we can replace Steel with the much less dense Titanium then we will save a lot of material, a lot of weight in the aircraft.

One of the alloys we have been looking at experimentally, is an alloy containing five weight percent Iron. As a lot of you know, Iron is a very difficult material to add to Titanium at these kinds of levels because it segregates; using the powder approach we're able to avoid this segregation.

Metal matrix composites, an area of great payoff, but an area which has been a challenge over the years. I do not have time to go into this in any great amount of detail but just to mention that both with the conventional Titanium alloys and with the intermetallic alloys, use of things like Silicon Carbide in titanium can improve the modulus and perhaps, by very judicious use, can also improve the lifetime of these materials in terms of providing a region which will cause cracks to divert rather than to propagate through the material.

Other advances which I will talk about just in one figure, is superplastic forming and diffusion bonding, a technique particularly applicable of course to sheet metal parts. Fig. 39 shows a B1B bomber, the version which is actually being built; the present door and a redesigned door using the superplastic forming and diffusion bonding techniques. The cost savings and the weight savings have been quite significant.

Isothermal forging, a technique which allows us to get close to net shape and to use Titanium so that we're able to do some of the things that I mentioned right at the beginning of the presentation, that is reduce the amount of Titanium which is used and also reduce the amount of machining which is required. In using that technique, it is possible to reduce the costs of components as shown in fig. 40 and 41, for a typical part using, as I said, the conventional and isothermal forging techniques.

I would like to finish by saying that I hope that I have been able to present to you today some of the areas where Titanium technology is advancing. The Aluminum alloys and organic composites are not sitting still; there are many advances. Aluminum alloys which are usable, as I said, to perhaps as high as 650 degrees Farenheit with strenghts as high as perhaps 80 or 90 KSI and with used density particularly Lithium additions same kinds of advances with organic composites. I have chosen the areas more interesting in my opinion, but everybody is entitled to his own selection of the areas which might see the biggest advances over the next few years. Thank you.

QUESTIONS:

1. Does Mr. Froes foresee any potential for mechanical alloying of Titanium powders.

The answer is very definitely: yes. In a presentation of this sort I of course have to cover many items very quickly which I did today, but certainly mechanical alloying is one of the areas where I see a lot of potential and in fact already at my laboratory we are doing some work, for example on Titanium, mechanically alloyed with additions such as Nickel and Copper which have very deep detecties, which means that they are very susceptible to production of amorphous phases. We're working in those alloys, we are also working with alloys which I had mentioned earlier, which are difficult to alloy with Titanium conventionally such as Lithium and Magnesium to try to reduce the density. So, yes I do see mechanical alloying being an area very fruitful for further exploration in the Titanium system, not only for conventional types of microstructural development using the mechanical alloying approach such as in the ODS, the Oxygen dispersion strenght and Nickel based materials, but also as I've emphasized, in terms of producing amorphous materials which perhaps might have some application, but structural applications will not be usable directly but after producing the amorphous state and then crystallizing material, they hopefully will have mechanical properties at reduced density levels which are usable.

2. I think one of the things that we will have to be concerned about when we develope some of these hopefully new and higher temperature materials are that we're going to have to coat the surface. My approach there is: let’s develope the alloys first, see if we can get improved alloys, then we address the question of how do we coat the materials. I’m unwilling to stop my research in developing improved alloys because there is a possibility that we may not have good coatings. I think that using an American expression we will cross that bridge when we get to it although of course, we are doing some preliminary work looking at coatings also. Good question.

PRESENTATION OUTLINE

- CONCENTRATE ON AEROSPACE USE
  - ADVANTAGES
  - DISADVANTAGES
- DISCUSS ASPECTS OF TITANIUM TECHNOLOGY
  - EXTRACTION *
  - MELTING *
  - WELDING
  - CORROSION
  - BETA/HIGH-STRENGTH ALLOYS *
  - HIGH TEMPERATURE ALLOYS
  - CASTINGS *
  - PM/RST *
  - MMC
  - SPF/DB AND ISOFORGING
- FUTURE PROSPECTS

Fig. 1

Material Temperature Limits

MATERIAL SYSTEM	TEMPERATURE (°F) [1]	
	CURRENT	ESTIMATED POTENTIAL (19)
CONVENTIONAL		
2000	250 - 300	250 - 300
7000	180	180
ALUMINUM - LITHIUM	250 - 275	275 - 325
HIGH TEMP ALUMINUM	350 - 550	450 - 650
ALUMINUM MMC	N/A	450 - 650
TITANIUM ALLOYS	700 - 900	1100 - 1300
TITANIUM MMC	700 - 900	1100 - 1300
THERMOSET RESINS		
EPOXY	250 - 275	250 - 275
BISMALEIMIDE	350 - 375	400 - 450
POLYIMIDE	500 - 550	500 - 550
THERMOPLASTIC RESINS		
PEEK	250	400
ULTEM	300	300
TORLON	450	450
FUTURE DEVELOPMENT		500 - 550

[1] FIRST TEMPERATURE - LONG TERM
SECOND TEMPERATURE - SHORT TERM

Fig. 2

1984 PRICES FOR TITANIUM PRODUCTS

PRODUCT	DOLLAR PRICE[a]
RUTILE (TiO_2)	0.20–0.25
TICKLE ($TiCl_4$)	2.00–2.20
SPONGE	3.00–4.25
INGOT	4.35–5.25
PREALLOYED POWDER	35.00
MILL PRODUCTS	
SHEET	15–30
FOIL	175
FORGINGS	9–12
PLATE	8–14
COMPONENTS	
CASTINGS	40–200
FORGINGS	100–300
SHEET METAL	35–100

[a] Per pound of titanium

Fig. 3

AIRFRAME WEIGHT PERCENTAGE OF TITANIUM

SYSTEM	EARLY DESIGN	FINAL CONCEPT
B1 (BOMBER)	42	22
F15 (FIGHTER)	50	34
C5 (CARGO)	24	3

Fig. 4

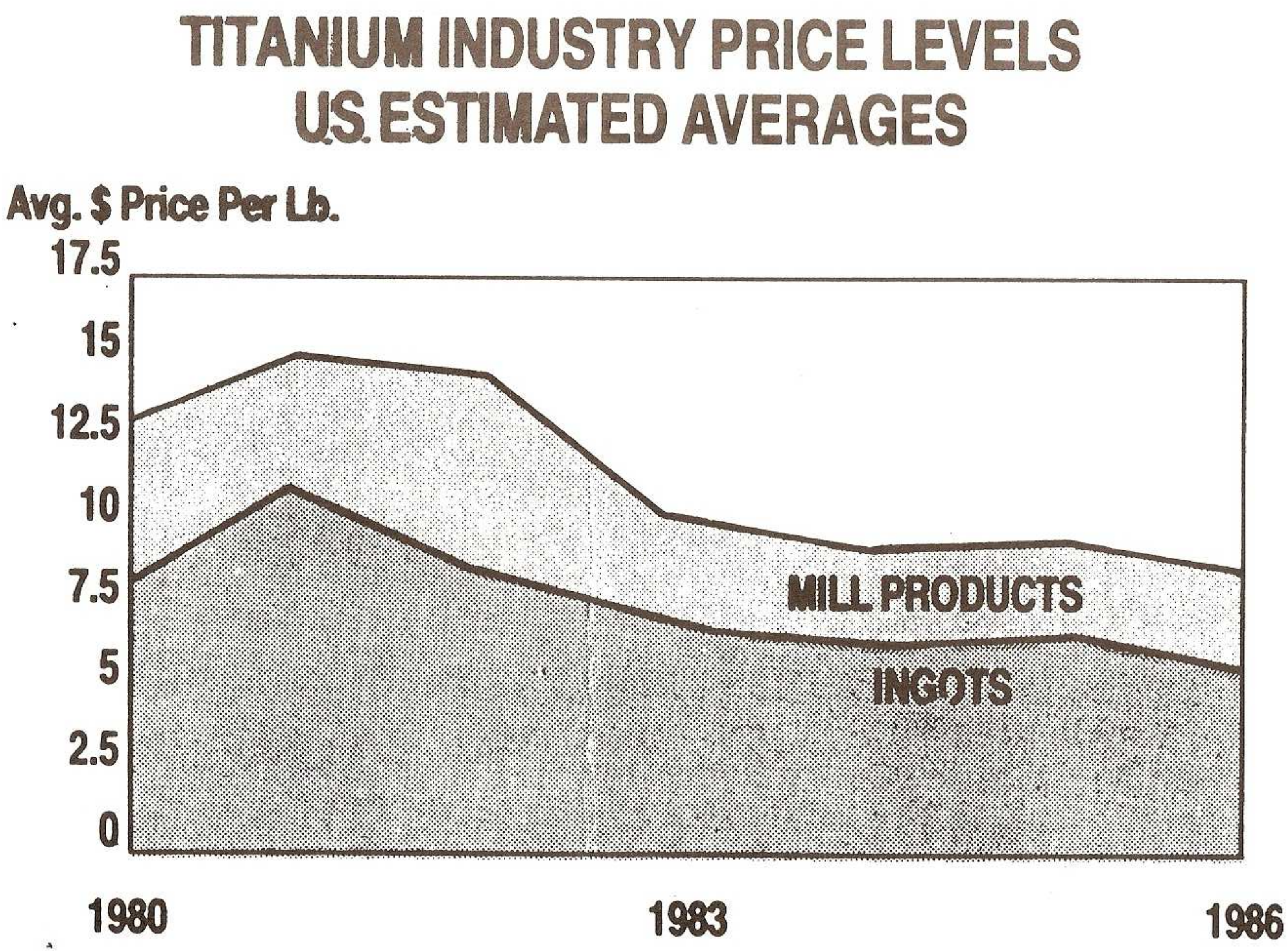
TITANIUM INDUSTRY PRICE LEVELS
U.S. ESTIMATED AVERAGES
Avg. $ Price Per Lb.
17.5
15
12.5
10
7.5
5
2.5
0
MILL PRODUCTS
INGOTS
1980
1983
1986

Fig. 5

MELTING TITANIUM

NEW TECHNIQUES

- NON-CONSUMABLE
- ELECTRON BEAM
  - — LOW PRESSURE REQUIRED
- PLASMA
- ELECTROSLAG
  - — CONTAMINATION A CONCERN
- INDUCTION SLAG
  - — BOM DEVELOPMENT

Fig. 6

BETA/HIGH STRENGTH TITANIUM ALLOYS*

- ALLOYS SUFFICIENTLY ALLOYED WITH BETA STABILIZERS (E.G., Mo, Cb, V, Fe, Cr) TO MAINTAIN A BCC STRUCTURE TO ROOM TEMPERATURE

- OFFER ENHANCED:
  - PLASTICITY (DUCTILITY)
  - STRENGTH
  - DEEP HARDENABILITY
  - GOOD FRACTURE TOUGHNESS/FATIGUE CRACK GROWTH RATE

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*SEE JOM VOL. 37, JANUARY 1985

F. H. FROES AND H. B. BOMBERGER

Fig. 7

PRESENT BETA ALLOYS

Ti-13V-11Cr-3Al (BETA I OR B120VCA)

- SR71 USE
- DIFFICULT ALLOY

Ti-11.5Mo-6Zr-4.5Sn (BETA III)

Ti-8V-8Mo-2Fe-3Al ("8-8-2-3")

Ti-3Al-8V-6Cr-4Mo-4Zr (BETA C)

- SPRINGS

Ti-10V-2Fe-3Al ("10-2-3")

- FORGEABLE /HIGH STRENGTH
- USE ON 757/767

Ti-15V-3Al-3Cr-3Sn ("15-3")

- FORMABLE SHEET ALLOY
- USE ON BIB

Fig. 8

MELTING TITANIUM *

- WELL ESTABLISHED CONSUMABLE VACUUM ARC METHOD
  - CURRENT CAPACITY IN USA ESTIMATED TO EXCEED 110M POUNDS
- QUALITY OCCASIONALLY A CONCERN
  - TYPE I ALPHA STABILIZED
    - HOUSE-KEEPING PROBLEM
  - ALLOY SEGREGATION
    - PARTITION COEFFICIENT, K
    - BETA FLECKS
    - TREE RINGS

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* SEE JOM DECEMBER 1984
H. B. BOMBERGER AND F. H. FROES

Fig. 9

HIGH TEMPERATURE TITANIUM ALLOYS*

- MAJOR USE IN GAS TURBINE ENGINES
  - WEIGHT ADVANTAGE OVER SUPERALLOYS
- DEVELOPMENTS TO DATE INCREMENTAL FROM Ti–6Al–4V
- FURTHER DEVELOPMENTS REQUIRE INNOVATIVE APPROACHES
  - ALUMINIDES
  - DISPERSOIDS (RS/PM)
- COATING ADVANCES PROBABLY NECESSARY

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* SEE JOM VOL. 36, DECEMBER 1984

D. EYLON, S. FUJISHIRO, P. POSTANS, AND F. H. FROES

Fig. 10

PREALLOYED MICROSTRUCTURES

- CONVENTIONALLY ELONGATED ALPHA LATHS

- CAN BE MODIFIED BY:

  — CHANGING COMPACTION CYCLE

    - hip
    - fluid die

  — STRAIN ENERGIZING

  — THERMOCHEMICAL PROCESSING

  — POST-COMPACTION WORKING

  — HEAT-TREATMENT

Fig. 11

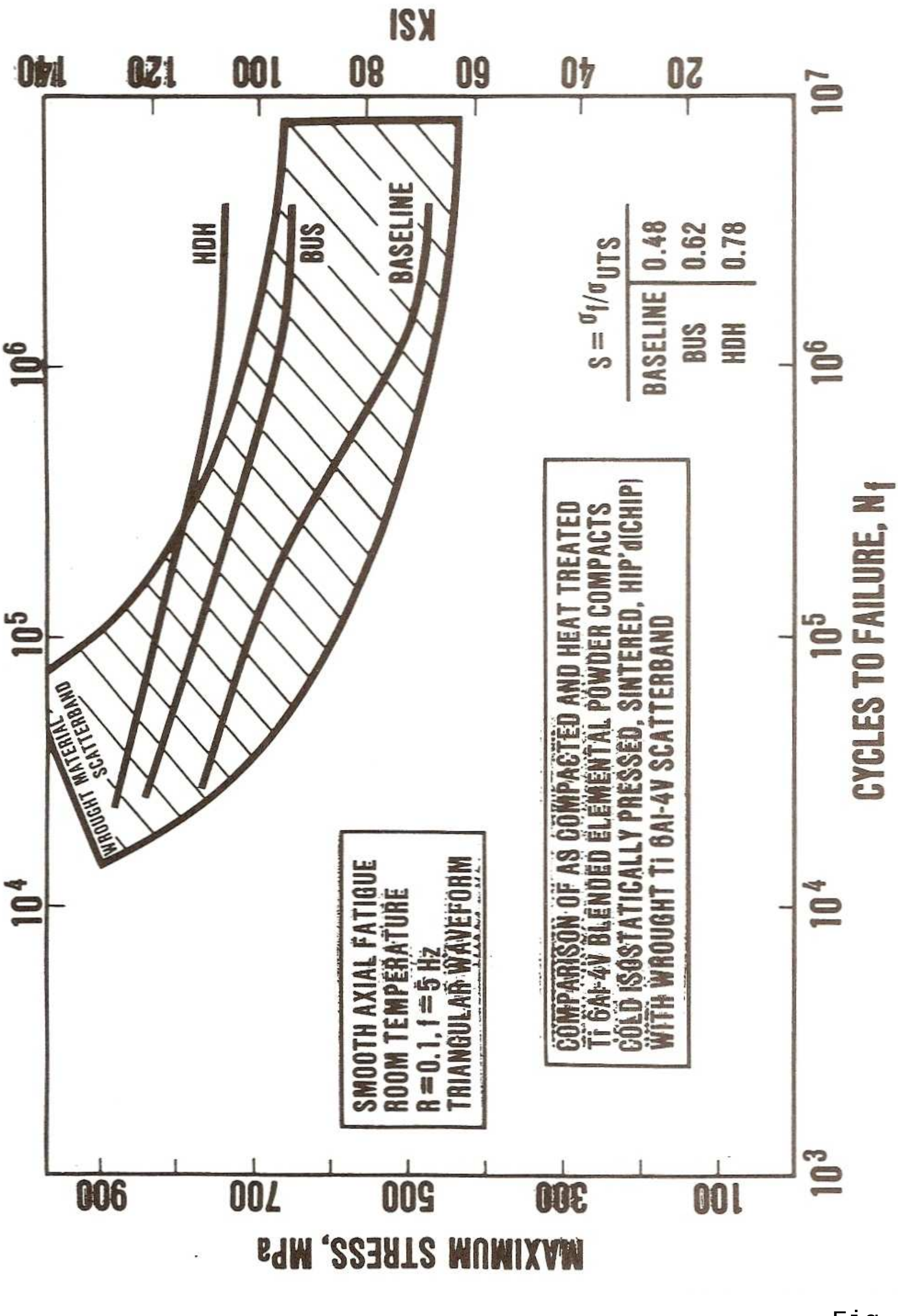

SMOOTH AXIAL FATIGUE
ROOM TEMPERATURE
R = 0.1, f = 5 Hz
TRIANGULAR WAVEFORM
COMPARISON OF AS COMPACTED AND HEAT TREATED
Ti 6Al-4V BLENDED ELEMENTAL POWDER COMPACTS
COLD ISOSTATICALLY PRESSED, SINTERED, HIP'd(CHIP)
WITH WROUGHT Ti 6Al-4V SCATTERBAND
WROUGHT MATERIAL SCATTERBAND
HDH
BUS
BASELINE
S = σf/σUTS
BASELINE 0.48
BUS 0.62
HDH 0.78
MAXIMUM STRESS, MPa
KSI
CYCLES TO FAILURE, Nf

Fig. 12

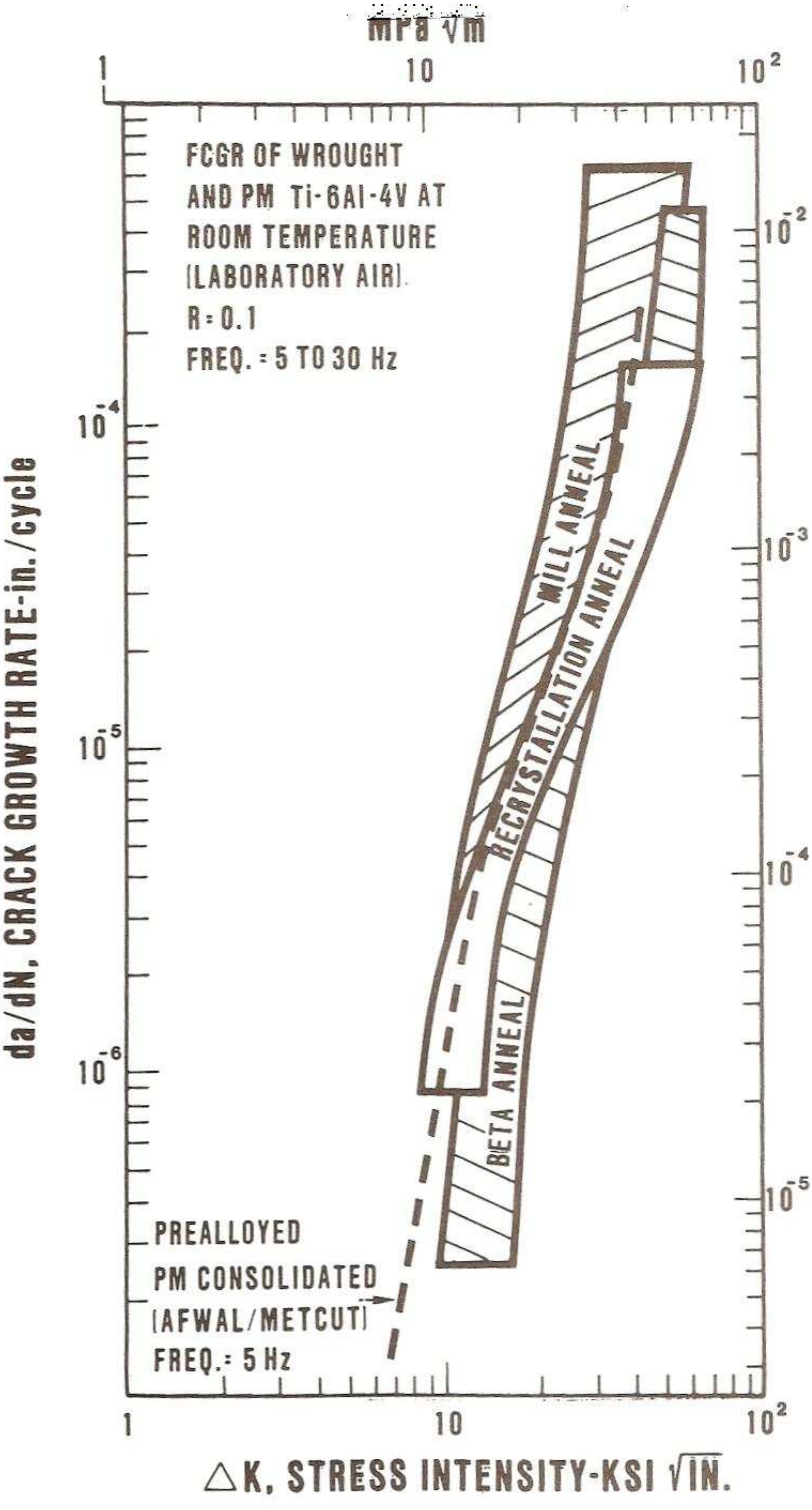
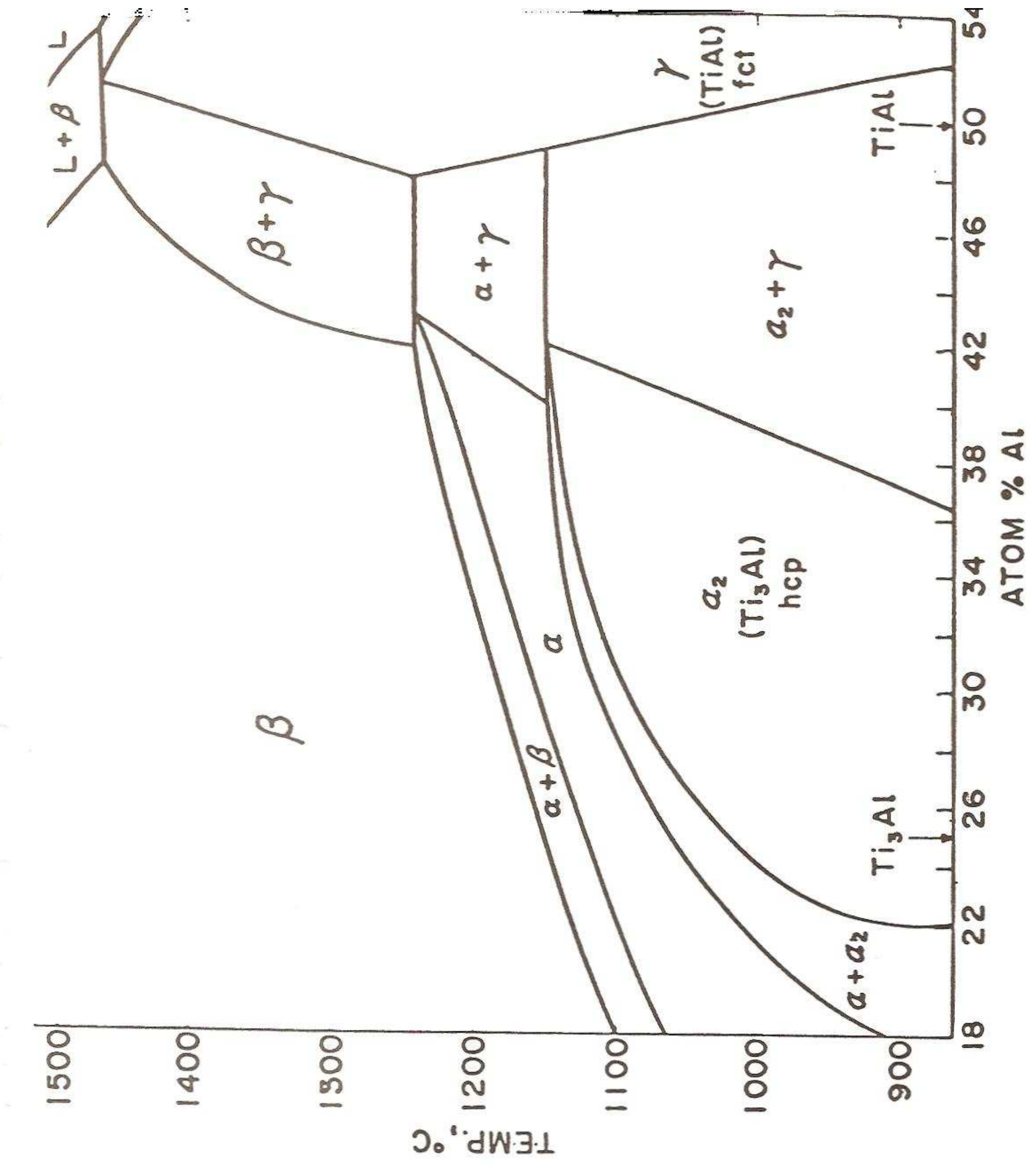

MPa √m
1
10
10^2
FCGR OF WROUGHT
AND PM Ti-6Al-4V AT
ROOM TEMPERATURE
(LABORATORY AIR)
R = 0.1
FREQ. = 5 TO 30 Hz
MILL ANNEAL
RECRYSTALLATION ANNEAL
BETA ANNEAL
PREALLOYED
PM CONSOLIDATED
(AFWAL/METCUT)
FREQ.= 5 Hz
10^{-4}
10^{-5}
10^{-6}
da/dN, CRACK GROWTH RATE-in./cycle
10^{-2}
10^{-3}
10^{-4}
10^{-5}
mm/cycle
1
10
10^2
ΔK, STRESS INTENSITY-KSI √IN.

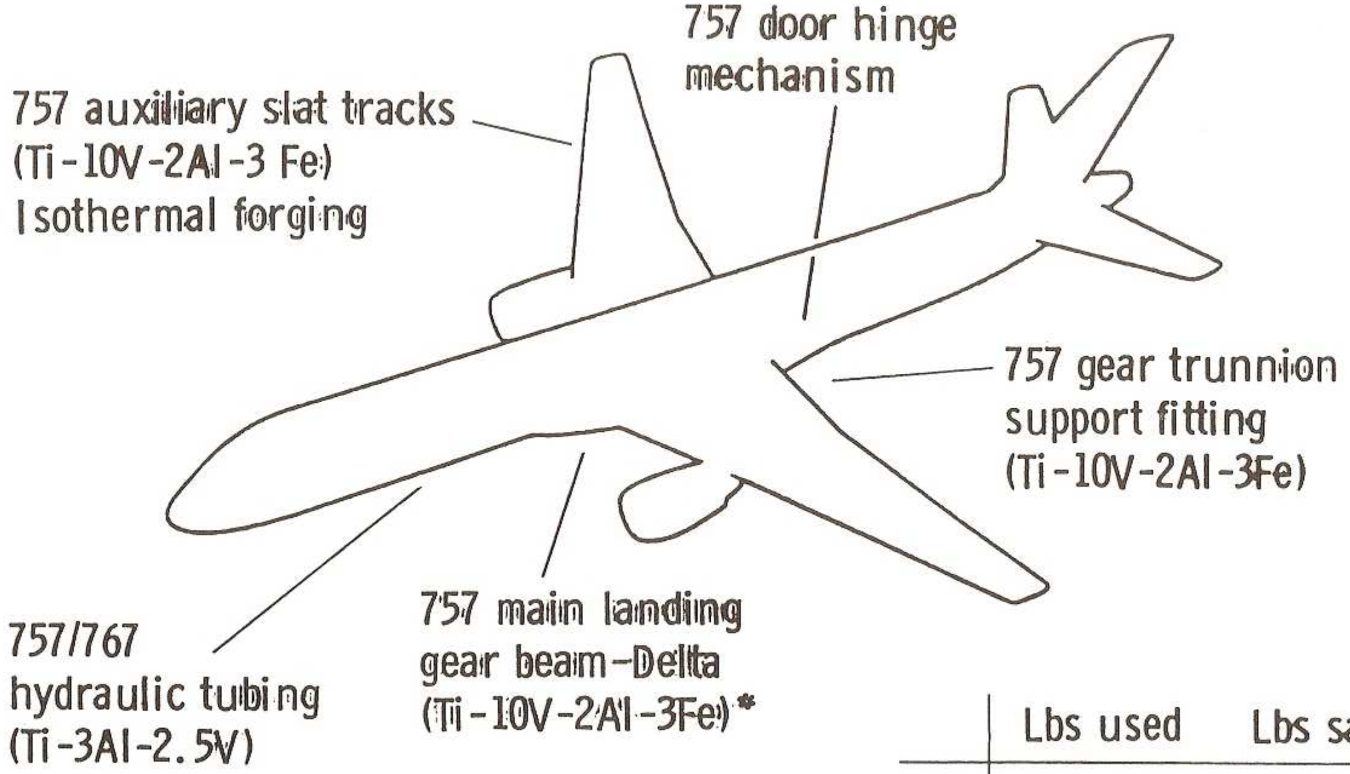
Fig. 13



L
L + β
β + γ
β
α + γ
α
α + β
α₂ + γ
γ (TiAl) fct
α_2 (Ti_3Al) hcp
$\alpha + \alpha_2$
TiAl
Ti_3Al
1500 1400 1300 1200 1100 1000 900
TEMP., °C
18 22 26 30 34 38 42 46 50 54
ATOM % Al

Fig. 14

Improved Titanium Alloys
757/767 Applications



	Lbs used	Lbs saved
757	409 (*1,509)	200 (*325)
767	360	145

*Not committed

BMT81-405-R1

Fig. 15

PRESENT BETA ALLOYS

Ti-13V-11Cr-3Al (BETA I OR B120VCA)

- SR71 USE
- DIFFICULT ALLOY

Ti-11.5Mo-6Zr-4.5Sn (BETA III)

Ti-8V-8Mo-2Fe-3Al ("8-8-2-3")

Ti-3Al-8V-6Cr-4Mo-4Zr (BETA C)

- SPRINGS

Ti-10V-2Fe-3Al ("10-2-3")

- FORGEABLE /HIGH STRENGTH
- USE ON 757/767

Ti-15V-3Al-3Cr-3Sn ("15-3")

- FORMABLE SHEET ALLOY
- USE ON B1B

Fig. 16

LANDING GEAR CONTRIBUTION TO TOTAL STRUCTURAL WEIGHT

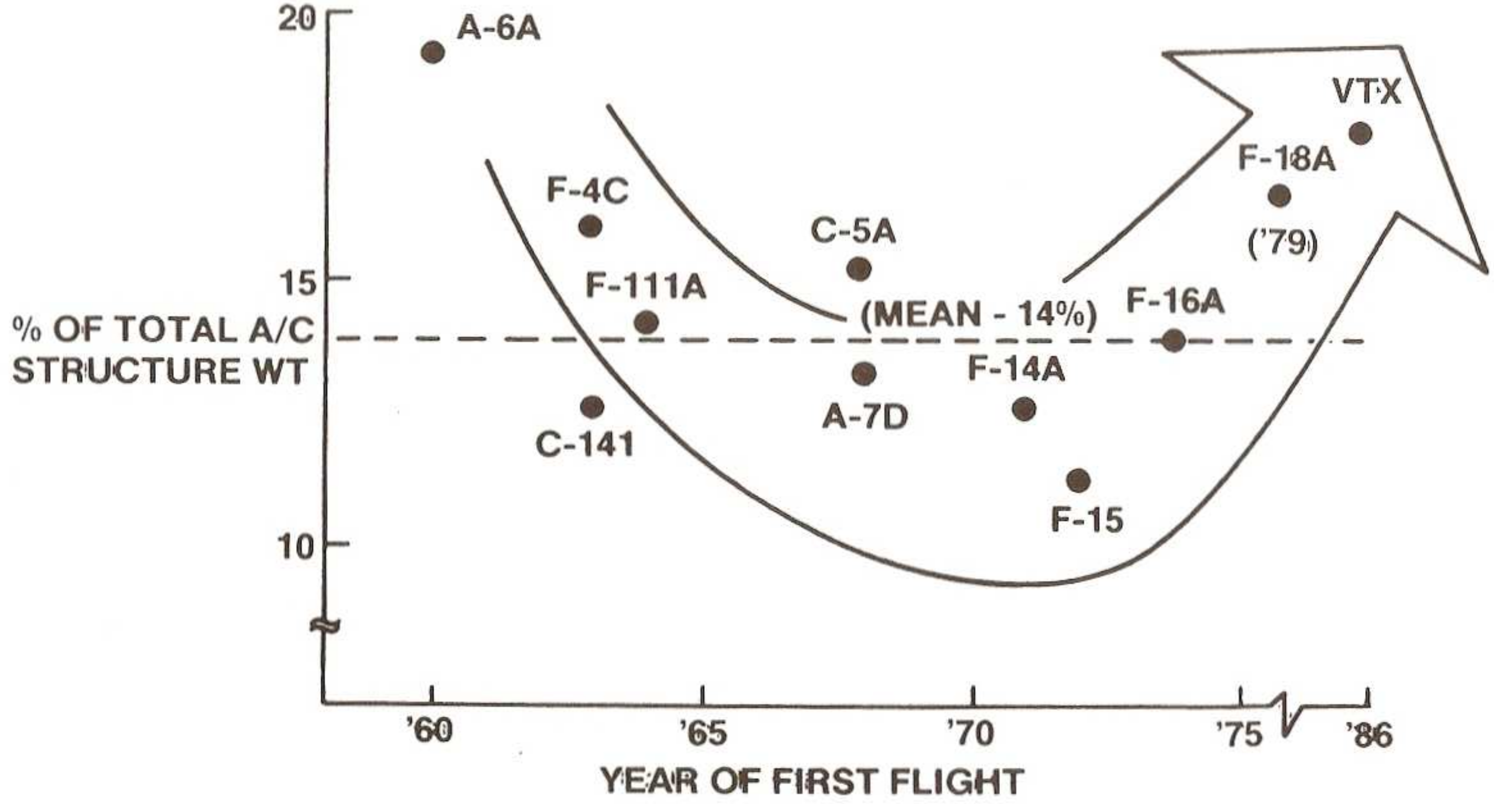


Fig. 17