Metallurgy, Forming and Welding of Titanium Alloys

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INTRODUCTION

Combination of high strength to weight ratio, good mechanical properties, corrosion resistance up to 600oC, good formability, age hardenability, ductility, creep resistance, and high corrosion resistance in marine environment, have led to a wide and diversified range of applications in defence, aerospace, welded propellant tanks, chemical plant, power generation, oil and gas extraction, jet engines, rocket parts, and other industries. Forging and processing of Ti-6Al-4V alloy elbows, tees, flanges, domes, and connections are done since 2004 at FFPL; supra-transus beta forging followed by sub-transus deformation were carried out. Titanium turning scrap as well as powder is pyrophoric. Thermal conductivity of Ti alloys is not good, and water quenching may initiate quench cracks in certain cases. Commercial titanium transforms from body centered cubic to (BCC) hexagonal close packed (HCP) structure at about 8900C.

Grouping of titanium alloys:

Titanium alloys are a unique class of material, they are strong as steel but have about 45% of its weight, with excellent high temperature corrosion resistance up to 600 0C, and excellent corrosion service life (35 to 40 years) in marine applications. The commercial titanium alloys are basically grouped in five types, distinguished by their chemical composition, properties and microstructures.

Commercial Titanium: They are commercially pure titanium alloys (i.e., 98 to 99.5% Ti, or ASTM grade 1), strengthened by small additions of oxygen, nitrogen, carbon and iron. These alloys are more ductile, readily forgeable and weldable by fusion welding, using ERTi-1 wires under controlled argon flow rates, and argon shield.

Alpha alloys: These are mostly single-phase titanium alloys containing up to 7% aluminum and a small amount (< 0.3%) of oxygen, nitrogen and carbon. They are single phase ductile alloys, have fewer problems in forging, and these alloys are fusion welded in the annealed condition in industrial applications.

Alpha + beta alloys: These alloys have a characteristic two-phase (alpha + beta) microstructure formed by the addition of up to 6.5% aluminum and varying amounts of beta forming constituents like vanadium, chromium and molybdenum. These alloys are formed by rolling/forging under controlled parameters to produce fine grained microstructure. These alloys are welded mostly in the annealed condition.

Near beta alloys: The Ni-Ti alloys contain a large amount of the beta phase in the microstructure, stabilized by alloying additions such as chromium, and they are formed under strictly controlled forging parameters.

Beta alloys: Elements like V, Mo, Mn, Fe, and Cr cause stabilization of beta phase in titanium, and typical beta alloys are Ti-2Al-11v-2Sn-11Zr (beta C) and ti-13 V-11Cr-3Al (13-11-3) alloys. These are high strength and high corrosion resistant alloys.

METALLURGY OF TITANIUM ALLOYS:

The alpha + beta alloys are age-hardenable, and they can develop combinations of strength, ductility, and creep resistance. Titanium alloys are generally sensitive to strain rates, and the mechanical properties can vary with rate of straining. Flash Forge Pvt. ltd. has also developed welding procedure for welding of titanium alloy fuel tanks. Microstructures developed in forgings at FFPL, with over 70% forging reduction, followed by air cooling or water quenching, and sub transus heat-treatment, illustrate very fine and equiaxed accepted grain structure.

The titanium alloys commonly used in industrial applications are listed in Table 1

Table 1: Common titanium alloys and their filler materials:

ASTM Grade	Alloy Composition	UTS (min) MPa	Welding filler alloys/ comments	
1	Ti-0.15%O_2	240	ERTi-1	Commercially pure
2	Ti-0.20%O_2	340	ERTi-2	
4	Ti-0.35%O_2	550	ERTi-4	
5	Ti-6Al-4V alloy	900	ERTi-5	most widely used alloy
7	Ti-0.20%O_2- 0.2%Pd	340	ERTi-7	
9	Ti-3Al-2.5V alloy	615	ERTi-9	Tubular components
23	Ti-6Al-4V ELI	900	ERTi-5	ELI Low interstitials
25	Ti-6Al-4V-0.06Pd	900	ERTi-25	Corrosion resistant

In Ti alloys, a wide range of variants can be produced by adjusting thermomechanical process parameters like forging reduction, hot working range and heat-treatment conditions. Forging trials with relatively lower forging reductions show little grain refinement.

Thermomechanical processing:

Thermomechanical processing of this alloy using a series of hot rolling and heat treatment route, shows a refined (α+β) microstructure. Our Study at FFPL indicated that the dynamic recrystallisation (DRX) occurred below the transus temperature, and sub transus processing involving heavy reductions produced fine grained equiaxed α and transformed β microstructure.

In our experiments, we ensured that a reliable β transus temperature is known and reviewed for each heat of product before heat treatment in high (α+β) range. The dynamically recrystallized grains are equiaxed and their mean grain size remains constant, grain growth does not occur during this process.

Relatively lower forging reductions show coarse grain structure, as shown in micro-report 3 and 4. At FFPL, control of α + β phase morphology in the microstructure was done by thermomechanical processing involving forging reduction, forging temperature range, cooling rates, and subsequent heat-treatment parameters to produce either lamellar, or fine grain equiaxed structure, or bimodal structure as used in industry. The relationship between changes in yield stress in alloys and grain diameter 'd' is given by the equation:

k/d 1/2,

'k' is a constant in the equation, depending on the nature of the alloy.

FORGING OF TITANIUM ALLOYS:

At FFPL, processing of Ti-alloy components were made by hydraulic forging in the temperature range between 850oC to 1000oC, followed by either air cooling or water quenching. In thermomechanical process experiments, rapid post forging cooling rates or air cooling were used after heavy forging reductions to obtain fine transformation products. Subsequent heat treatments were done at sub transus temperatures in (α+β) phase, followed by aging, if required to increase strength. Titanium alloys can be deformed in superplastic temperature ranges above 850oC, with relatively less force.

At FFPL, experimental processing of Ti-alloy components were done by hydraulic forging in the temperature range between 950oC to 850oC, followed by either air cooling or water quenching. The chemical composition and mechanical properties of our alloy is shown in table-2 and table-3.

Table-2

- Chemical Composition of our alloy
- Al: 6.14%
- V: 3.98%
- O: 0.15%
- H: 0.002%
- Fe: 0.06%

Table-3

- Mechanical properties (Raw material)
- Yield Stress: 903 MPa
- Tensile Strength: 970 MPa
- Elongation %: 16%
- Reduction in area: 43%

TITANIUM WELDING TECHNOLOGY:

Welding of titanium alloys by various argon arc welding processes (TIG or MIG) is most widely practiced, and good service performance of weldments is proven. Newer joining methods, such as electron beam welding, under a high vacuum (10 -6 Torr), in E.B. welding Chamber, using 20 -100 KV high energy electron guns, and laser welding for ultra thin sections, have been successfully adapted for titanium. E.B. welds show shiny white appearance, when done in proper vacuum. Weld metal volume must be restricted to minimum to avoid excess heat input.

Titanium welding is different from most other types of GTAW as the need for an argon cover on the weld's back side. When titanium is heated in air, brittle oxygen rich alpha-case can form on the surface. FFPL has developed process sheets for performance test of forgings and valve fittings, and qualified as per ASME B 16.9 and ASME B 31.3. Typical welding parameters for titanium are enlisted in table-4, and tensile properties are shown in table 5.

Filler wire alloy compositions for welding titanium:

Titanium and its alloys can be welded using matching filler compositions given in AWS A5.16-2004 specifications. When welding higher strength titanium alloys, fillers of a lower strength are can be used to achieve adequate weld metal ductility. Recommended filler wires for welding some commonly used titanium alloys are listed in Table 1.

WELDING PREPARATIONS IN Ti :

Weld preparation must include removing surface oil, grease, dirt, or grinding dust from the areas to be joined. Cleaning with hot steam or an alkali degreasing in a dilute solution of sodium hydroxide can remove most of these oily contaminants.

To ensure that no moisture has condensed on the surface to be welded, we blow hot air on the surfaces. We can not overlook the fact that rubber gloves may contain chlorine as part of a vulcanizing process, and as such, lint-free gloves are to be used.

Purity of argon gas :

The argon gas for welding titanium should be very pure, and the main contaminants are oxygen, nitrogen, and moisture. Even if the argon is as pure as the 50 parts-per-million (PPM) range, some yellow-straw discoloration can occur.

Many welding establishments try to maintain a maximum of 10 to 20 ppm contamination level during welding. If the color begins to become dark, or if it exhibits any light shade of blue, it shows that the argon isn't pure enough. We start the argon gas flowing for a few seconds before using the high-frequency arc start. If we have enough shielding and the argon is being dispersed evenly over the surface, we should see a uniform color.

Glove boxes:

When titanium is heated, brittle alpha-case can form on the surface. Glove boxes offer an economical answer for effective argon cover. For parts too complex to fit through the glove box, special flexible polyethylene plastic bags or tents, complete with attached gloves, can be used.

TESTS ON TI WELDMENTS:

Macrostructure:

The macrostructure of weldments, made by macro-etching, should not show voids, and weld porosity should be controlled. Any foreign material inclusion in the weld is to be noted.

Microstructure:

The weld microstructure should be studied in details, including the heat affected zone (HAZ). Any layering or unusual microstructure should be reported with corresponding metallography.

Table 4- Some welding parameters of Ti

Thickness of sheet	=	13 mm,
Electrode diameter	=	3.2 mm filler,
Current	=	175-275 A,
Voltage	=	11-15 V
Speed	=	150-150 mm/min, 5-6 passes

Table-5 - Typical tensile properties of TIG weldments in Ti

Alloy	Tensile strength (MPa)		Proof stress (MPa)		Elongation %	
	Parent	Weld	Parent	Weld	Parent	Weld
ASTM Grade 2	460	510	325	380	26	18
Ti-6Al-4V Grade 5	1000	1020	900	880	14	8
Ti-3Al-2.5V Grade 9	705	745	670	625	15	12

Tensile testing of welds:

The weldments can be tensile tested for proof stress and UTS. The welds should have comparable strength and percent elongation as the parent metal, in longitudinal and

transverse direction. Any deviation may be reported for approval.

Hardness tests:

Hardness contour should be recorded on weld and heat affected Zone (HAZ). The hardness of weldments should be comparable to the parent metal, otherwise, stress relieving or annealing will have to be done.

Visual and dimensional inspection:

Dimensions, warpage/distortions, line defects, undercuts, lack of penetration, warpage/distortions, and lack of fusion are checked at weldments.

Liquid penetrant test:

Weld edge preparation of components/ fittings are examined by LPT test. The tests are performed according to ASTM SE-165, or customer specifications.

Hydraulic proof test (Design test):

Hydro-test at specified pressure is carried out at FFPL, and no leak is permitted during proof pressure test reference to ASTM B16.9, B31.3. The net volumetric stretch should not exceed 10% of total increase in volume recorded at proof pressure.

NDT test:

NDT tests are carried out before and after proof test, and compared with pre-proof stress details. No change in details is permissible.

Helium leak test:

Helium leak test is conducted as specified by customer in the component drawings. Permissible leak rates are in the range of 6.5x 10 -9 m 3 Pa/sec.

Radiography:

To ensure a sound weld, the weldments are to be checked by radiography for probable defects and cracks, if required.

COMMON DEFECTS IN TITANIUM WELDS:

Titanium and its alloys can be fusion welded provided a proper choice of welding method is made and suitable precautions are taken. TIG, E.B. welding and plasma welding processes, with argon or argon-helium shielding gas are used.

Weld metal porosity:

In titanium, hydrogen from moisture in the environment or due to contamination on the filler and parent metal surface is the most likely cause of porosity

Gas rich surface layer

The exposed weld surfaces are richest in gases and inadequate argon/helium gas flow in welding can lead to formation of hard and brittle alpha case, which may be responsible for cracking in service life.

Weld discontinuities and voids:

Weld discontinuities lower the mechanical properties of weldments. Voids arise when gas bubbles are trapped between dendrites during solidification.

Gas embrittlement:

Weld embitterment can be caused by weld metal contamination by either gas absorption from the surrounding contaminants such as dust particles (mostly iron and iron oxides) on the surface.

Impurity contamination led cracking:

If iron or metal oxide particles are present on the weld surface, they dissolve in the weld metal impairing corrosion resistance and, at high iron content, it can cause embrittlement. Structural fabrication or welding of steel should not be done in the room for titanium welding.

Lack of fusion and layer formation:

This problem arises from inadequacy of the welder or the welding equipments. Mottling or swirling can be observed on improperly done weldments.

PRECAUTIONS IN TITANIUM WELDING:

Titanium is a highly reactive metal that forms compounds with most gases leading to unacceptable properties. Pre heating, controlled cooling, and stress relieving is recommended in most cases. When titanium is heated in air without proper precautions, the weld surface contains brittle carbides, nitrides, and oxides, each of which can reduce the fatigue life and notch toughness of the weld and heat-affected zone (HAZ). It is necessary to protect the weld surface, and also protect the back side of the weld, which is equally sensitive.

Whenever the welded components or fittings get heated to a temperature in excess of 500 degrees C, brittle oxygen rich alpha phase (or α-case) can form on the weld surface and its back side, and argon flow must be regulated to form a complete cover on the weldments.

CONCLUSIONS:

1. High-purity argon, clean work surface, clean working areas free of combustibles and grinding debris.
2. Adequate flow of argon gas for shielding and trailing cover is a must on Titanium weldments.
3. Our experience is that heat input to the weldments, and job temperature must be controlled.
4. Moisture and organic contamination from bare hands are to be minimized for titanium processing.

5. Selection of proper filler wire composition is very important for titanium welding.

6. The two processes for grain refinement by TMT are dynamic recrystallization and globularization.

7. Hydraulic forging can avoid overheating in forging process in Ti-6-4 alloys.

8. Dynamic recrystallization (DRX) during hot working at sub transus temperature, with higher forging reductions. The dynamically recrystallized grains were refined.

9. Proper preparation of surfaces to be welded, to make a clean, uniform, dry weld area is necessary.

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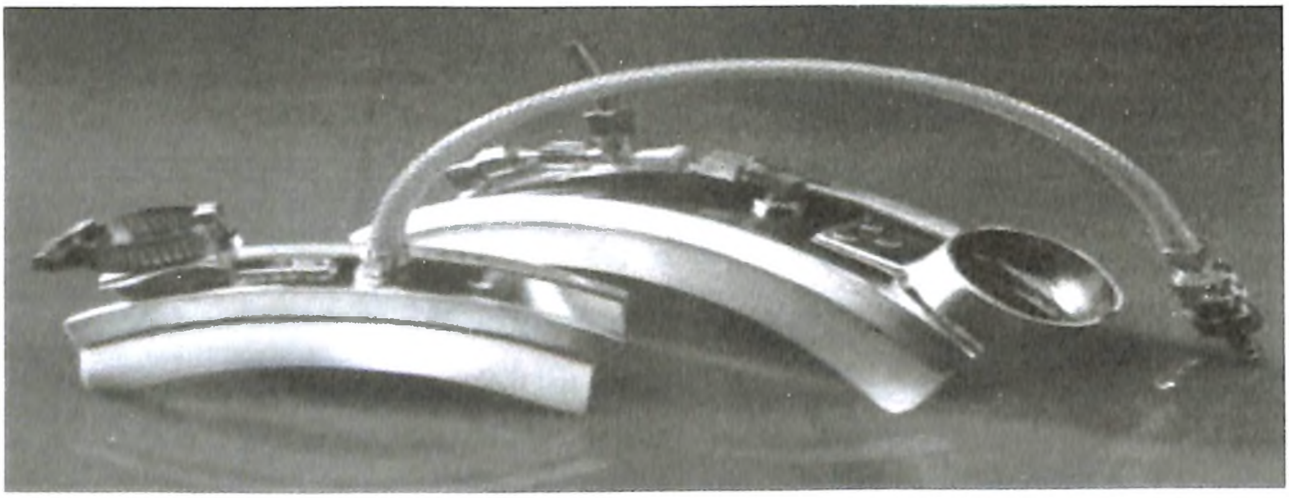
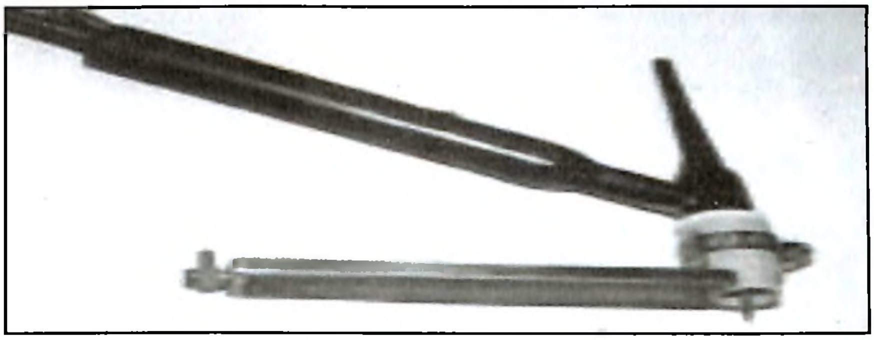
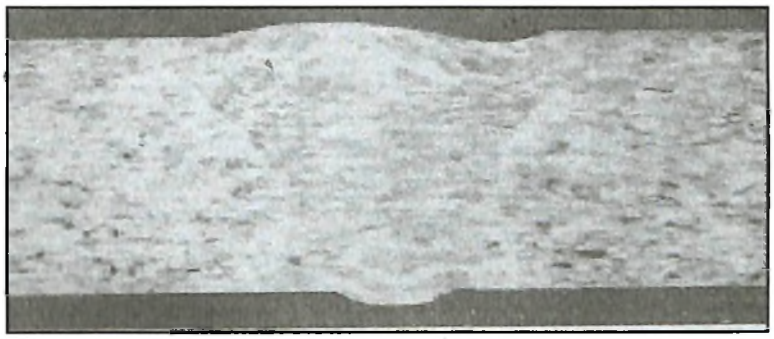


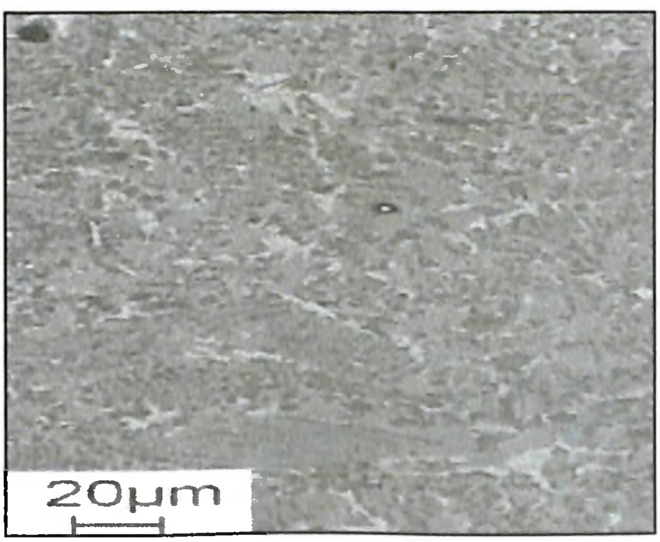
Typical argon gas flow trailing shield cover (Huntington fusion techniques).



Typical TIG torch with trailing argon cover assembly.



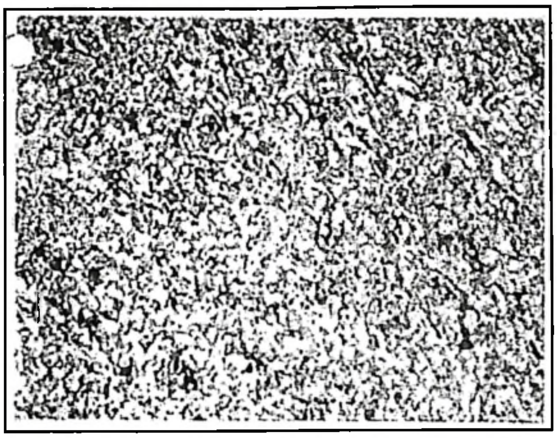
Electron beam welding under vacuum in Ti 6Al 4V alloy.



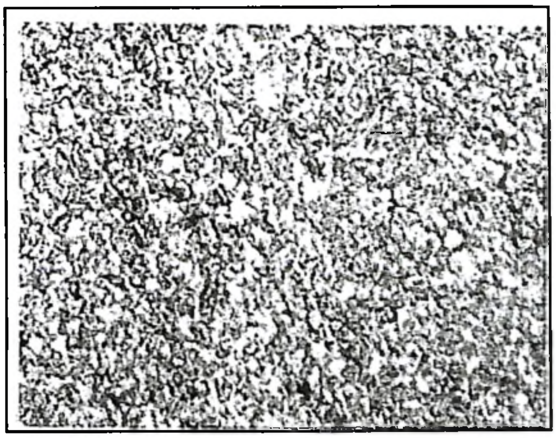
Micro report 1: Fine grained structure produced in Ti-6 Al 4V alloy by heavy forging reductions, X 500.

MIG welding in Ti 6Al 4V alloy under argon gas cover.

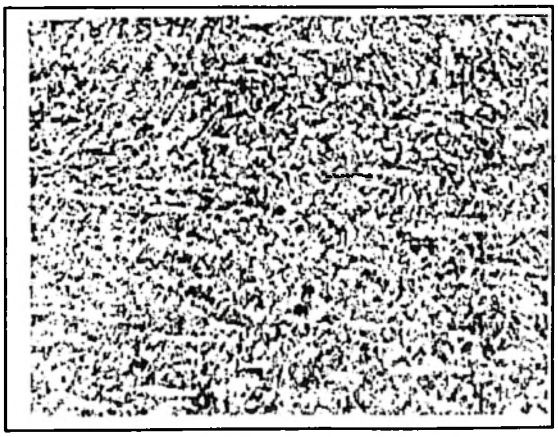

FLASH FORGE (P) LTD
CONCENTRIC REDUCER
SIZE : 4x10"



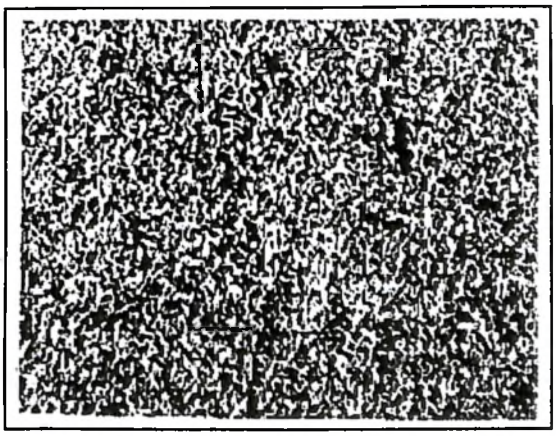
Dia : 185mm, Etchant : Kroll's reagent, Magnification 200X
Alpha and transformed beta grains



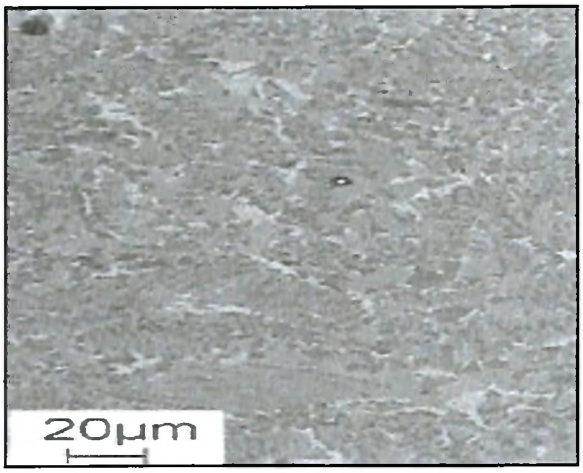
Dia : 225mm, Etchant : Kroll's reagent, Magnification 200X
Alpha and transformed beta grains



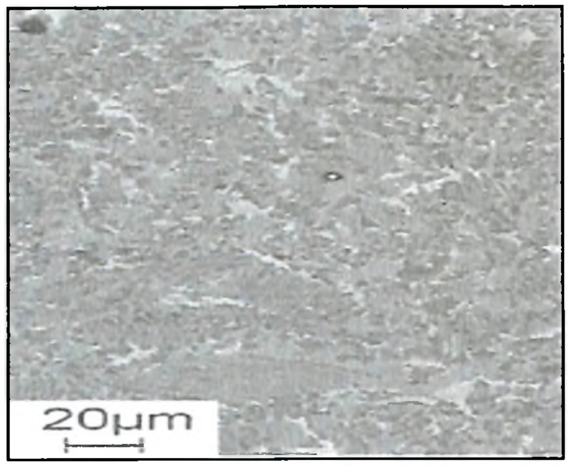
Etchant : Kroll's reagent, Magnification 200X
Transformed alpha and beta grains



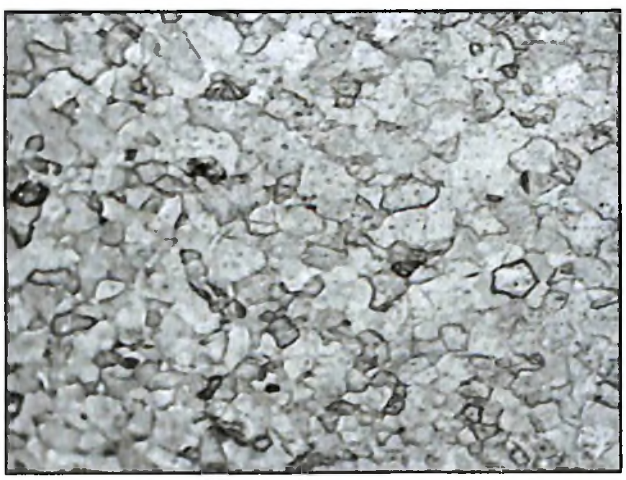
Etchant : Kroll's reagent, Magnification 299X
Equiaxed alpha and bets grains



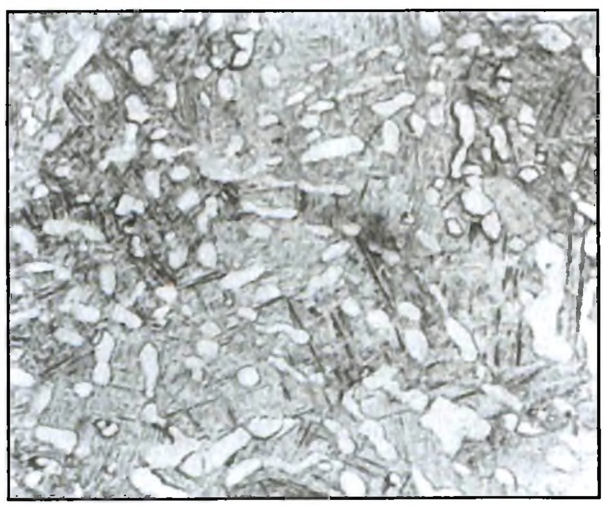
Micro report 1: Fine grained structure produced in Ti-6 Al 4V alloy by heavy forging reductions, X 500



Micro report 2: Fine grained structure produced in Ti-6 Al 4V alloy by heavy forging reductions, X 500.



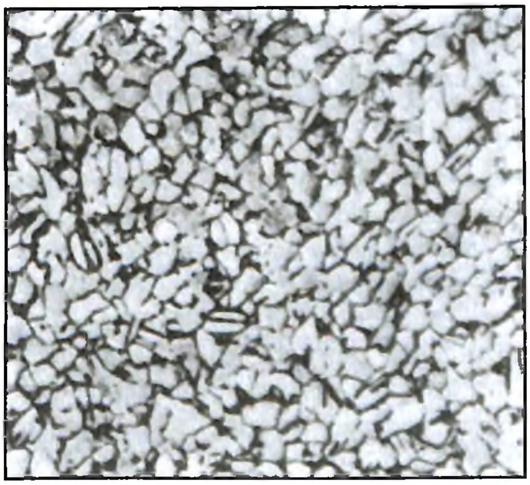
Micro report 3: Coarse grained structure produced in Ti-6 Al 4V alloy, by annealing at 9500 C, X100.



Micro report 4: Alpha and alpha prime Ti-6Al 4V alloy forged at 9500C, and water quenched, showing primary, X 100.

Micro report 5: Ti-6Al 4V alloy forged at 1000°C, and air cooled, showing coarse lamellar primary alpha X 100.

Micro report 6: Coarse grained elongated structure produced in Ti-6 Al 4V alloy, by light forging reduction, annealed, X100.



Microreport-7: Coarse equiaxed grain structure in Ti-6Al-4 V alloy with lower forging reductions at 950°C, followed by furnace cooling X 100