

THERMOMECHANICAL PROCESSING OF TITANIUM ALLOYS

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1 - INTRODUCTION

The series of international conferences devoted to Titanium has had a long tradition of excellence in the progress of this field of metallurgy. After London in May 1968, Boston in 1972, Moscow in 1976, Kyoto in 1980, Munich in September 1984, it is now France's turn to organize this 6th world congress at Cannes.

I hope that the choice of the city of Cannes on the Mediterranean coast will permit our foreign friends to discover and become more familiar with some of the regional riches of our country. You all know of the annual film festival which ended just two weeks ago. Today, it is time for the Titanium festival.

As Vice President of the Executive Committee, I would like to add to President Lacombe's opening address, the privilege I feel in sincerely welcoming each of you at this 1988 Titanium summit, and tell you how agreeable it is to see such a large attendance at this opening session.

During the last Congress in Munich, the Titanium industry was in the depths of the most severe recession it has ever known, after the 1980-1981 boom years. Recovery has taken place gradually, and today, we can regard the present demand with much more confidence than four years ago, even if we still not have reattained the level of 1981.

Before approaching the subject of thermomechanical processing of Titanium alloys, I would like briefly to describe the present situation of the Titanium industry in France in terms of its production and main applications, and give an over-view of the scientific and technical potential of research in the this field.

2 - THE TITANIUM INDUSTRY IN FRANCE

Beginning by the first link in the production system, France is not at present producing Titanium sponge. There were two Titanium sponge plants in France, but these had to close down production respectively in 1958 and 1962 in the face of foreign competition.

France has only one Titanium producer, the PECHINEY Group's CEZUS Company, which smelts Titanium sponge and scraps and produces alloys which are transformed into long products: billets, bars, tubes and wire, with a special place for fastener stock and flat product manufacture: plate, sheet and strip. With its 5 consumable electrode vacuum melting furnaces and one non-consumable electrode melting furnace, the capacity is 4,000 tons of ingot per year. The standard 5-ton ingot has a diameter of 830 mm; the largest ingot can weigh up to 15 tons. Transformation of ingots is made mainly by forging with a new 2,500-ton, fully automated press, which we will describe in further detail during this exposé, and continuous train hot rolling, extrusion and cold rolling, wire drawing and swaging.

France also has a strong precision forging and drop forging industry with at least five major forging companies experienced in forging of Titanium, as well as other metals such as steel, superalloys and aluminium alloys. These produce the complete range of forgings required for the aerospace industry and other industrial applications, both for standard alloys and new alloys under development.

The equipment and apparatus produced, in particular for chemical engineering and energy production, are produced in terms of the most recent specifications of the state of the technique. Simultaneously, advanced technologies are used in the aerospace industry with, for example, isothermal die forging and components formed by superplasticity forming and diffusion bonding (SPF/DB).

In France, consumption development is balanced well with approximately 60% for aerospace and 40% for industrial applications.

From the aerospace viewpoint, there are two leading aircraft engine manufacturers in France, Snecma and Turbomeca, and two major aircraft constructors: Aérospatiale and Avions Marcel Dassault.

After having produced the Atar engines, which equipped all the Dassault Mirage aircraft series, Snecma is now producing the M 53 engine for the Mirage 2000 (approximately 5 engines per month) and is developing the new M 88 engine intended for the future Dassault combat aircraft, the Rafale.

From the civil aviation engine viewpoint, Snecma is producing the CF 6-50, CF 6-80 and CFM 56 engines in common with General Electric, and is participating in the development of a contra-rotating propeller engine, the UDF GE 36. For the series of CFM 56 engines, present production of which is exceeding 55 engines per month, Snecma is engaged in a joint venture with G.E. on a 50-50 basis.

Turbomeca produces two engines in collaboration programs: the Adour, in collaboration with Rolls-Royce for the Jaguar fighter, and the Larzac, with Snecma, MTU and KHD in West Germany for the Alphajet aircraft. In addition Turbomeca is producing a wide range of engines for helicopters and turboprops.

Aérospatiale is a member of the Airbus Industrie Consortium producing the Airbus aircraft family, with production now exceeding 7 aircraft per month. The Airbus A.320 (150 seats) is a major success. Today, the level of firm orders and options represents 311 A.300's, 156 A.310's and 461 A.320's. Moreover, Aérospatiale produces helicopters and has, with the Italian company Aeritalia, started construction of the ATR 42 commuter plane (42 seats) using an important quantity of Titanium alloys (more than 250 aircraft ordered).

Avions Marcel Dassault not only produces the well-known fighters of the Mirage family (production rate 4 aircraft per month), but also the Falcon series with 230 aircraft already delivered for the Falcon 10 and 100, 506 aircraft for the Falcon 20 and 200, and 212 aircraft for the Falcon 50 and 900.

Non-aerospace applications are also highly developed in France, both in chemical engineering, medical prostheses, plate exchangers, geophysics and the petroleum industry, steam turbine blades etc. In particular, the production of condensers using sea water or polluted waters as a cooling fluid must be mentioned, especially for all the coastal nuclear power stations (approximately 140 tons of tubes for an installed power of 1000 electrical Megawatts). Also, as an example of naval applications, we should mention the Ti-6Al-4V hull of the French submarine "Nautilus", a bathyscaphe capable of diving down to 6,000 meters for submarine exploration. Lastly, subsequent to the use of Titanium in the competition automobile field, new developments are expected for parts such as link rods, valves, springs and torsion bars for series production automobiles.

This intense engagement in Titanium from the industrial viewpoint is accompanied by extensive research and development activities, both in universities and public research centers, and in applied research in industrial research centers. This can be observed from the 70 French papers presented at this congress. Time is too limited to give a general view of this research activity. However, in the field of recent research, we should mention:

- the study of microstructures and the development of new alloys with Snecma, the Conservatoire National des Arts et Métiers, the Technology University of Compiègne, Onera and CEZUS,
- analysis of surface treatments, research on resistance to oxidation and corrosion, with the University of Orsay, the research center of Vitry, the Technological University of Compiègne, the Toulouse School of Chemistry, the Armament Central Technical Establishment and the Strasbourg School,
- production of liquid metal, with the "Ecole des Mines" at Nancy and INSA at Rennes,
- the properties of use, with the Mechanical Engineering School of Nantes, the Ecole Centrale, INSA at Lyons and CEAT at Toulouse.

Moreover, the recent creation of a Titanium Scientific Group for the study of hot deformation, thermomechanical processing and relations with the structure and properties of use should be mentioned. In this cooperative action, the "Centre National de la Recherche Scientifique" and industry are combining their efforts with a heavy concentration of facilities over 4 years. This scientific group consists of research teams from:

- 5 industrial companies: Aérospatiale, CEZUS, C3F, Snecma and Turbomeca
- 5 university partners, the Mining Engineering Schools of Paris, Nancy and Saint Etienne, the metallurgical laboratory of Orsay and the Conservatoire National des Arts et Métiers.

Finally, forgeability of materials and deformation rheology have been widely studied in France by several research teams, including:

- the UGINE research center (1 to 11)
- IRSID (12 - 13)
- the Paris Ecole des Mines (14)
- the St Etienne and CEMEF Ecole des Mines (15 to 19)
- the Nancy Ecole des Mines.

3 - THERMOMECHANICAL PROCESSING AND SPECIAL METALLURGICAL FEATURES OF TI ALLOYS

3.1 Hot forming is a major stage in the manufacturing cycle of Titanium alloys since, with heat treatments, it notably affects the structure and properties of use of the final product.

All hot forming is thermomechanical processing. However, this term is normally used only when strain and temperature conditions are controlled and selected in order to improve the structure and properties of the product, and which would otherwise be impossible with the alloy under consideration.

3.2 Titanium alloys are very sensitive to their metallurgical history. This particularity of their behavior is due mainly to the special character of allotropic transformation, and the resulting structural heredity. Therefore, it is necessary to allow for relationships between the mechanical characteristics, the structure and the transformation procedures, if it is desired to optimize the final properties of use. For example, the acicular structure is particularly favorable for creep, fracture toughness, expressed by the stress intensity factor K_{1C} and resistance to fatigue crack growth due to low cycle fatigue. Conversely, for high cycle fatigue, crack initiation is the important factor, and it is necessary to seek stable, fine grain equiaxed structures.

3.3 Also, it is necessary to mention the special physical properties of Ti alloys. In all hot-forming operations, temperature evolution at any point of the product will depend:

- on the initial heating temperature
- on surface heat losses due to radiation and convection in the atmosphere and due to contact with the die or working tool
- heating, related to working, which can be estimated by local plastic strain: $W = \int_0^{\bar{\epsilon}} \sigma(\tau) d\bar{\epsilon}$ and the resulting temperature increase:

$$\Delta T = \frac{W}{\rho C_p}$$

Ti and its alloys present a specific heat C_p , for all temperatures, which is relatively high with respect to steels (fig. 1). Conversely, heat conductivity λ is particularly low: this may be compared to that of austenitic stainless steels, and is ten times lower than that of aluminium (fig. 2).

Given the lower density ρ of Titanium, significant heating ΔT of the material can result during working. Here is an example of several values at 700°C:

Metal	C_p	ρ	ρC_p
Zr	350	6.5	2,275
Ti	800	4.5	3,600
Fe	800	7.8	6,240
Stainless steel 18-8	600	7.9	4,740

This risk of heating, which may be even more marked in the case of localized working, may bring the metal to a temperature higher than transus $\alpha + \beta / \beta$

3.4 Knowledge of hot strength and flow laws depend on determination of flow stress σ of the metal, and on ductility before localization of deformation. The flow stress σ enables the working forging, rolling or extrusion forces to be known and these processes to be modeled.

This workability greatly depend on strain rate and figure 3 shows this diversity against working method. The bottom part of this figure also lists the available experimental techniques and their limits of use.

The hot workability, represented by σ , is a function of numerous parameters, including:

- the composition and type of the alloy
- the initial structure
- the deformation temperature T , true strain or forging reduction $\frac{\bar{\epsilon}_0}{S}$
- the true strain rate $\dot{\bar{\epsilon}}$
- the working mode and sequences
- the post-working cooling mode and further heat treatments.

4 - HOT WORKABILITY OF ALPHA - BETA ($\alpha - \beta$) TI ALLOYS

4.1 - Transformation range

In the simplest range (sequence 1 of figure 4a), hot transformation of alpha-beta alloys consists of two successive steps:

- Rough working of the ingot is always performed in the beta range at a temperature generally between 1000 and 1150°. In this manner, the adequate hot workability of the beta phase and the lower working energies are used to destroy the coarse and fragile structure of the as-cast condition. But, if working in the beta phase generally involves few problems, the subsequent cooling is of major importance, since this leads to coarse acicular microstructures, which do not permit satisfactory utilization properties at ambient temperature (for example tensile elongation).
- It is for this reason that a finishing step is always used. This consists in applying a forging reduction $\frac{S_0}{S}$ higher than 4 in the alpha + beta phase. The heating temperature is approximately 50° lower than the transus temperature, and the hot workability is notably less, as will be seen below. But, much more efficient forging enables a satisfactory equiaxed micrographic structure to be obtained after recrystallization during subsequent annealing.

We shall now examine the intrinsic forgeability of the Ti-6Al-4V alloy. At present, this alloy is the most widely used and, for this reason, the best known and most studied. Analysis of rheology and structural changes during hot forming is not, however, specific, and can be extrapolated to other alpha-beta alloys.

4.2 - Effect of cooling mode from beta on structure

Due to very rapid recrystallization of the beta phase, the method of cooling after work is decisive for final structures:

- water quenching leads to an alpha martensitic structure (fig. 5a)
- air cooling, delayed quenching and slower and slower cooling leads, on the one hand, to the grain boundary alpha on the boundary of ex-beta grains, and to a breakdown into a family of alpha platelets which thicken with the slowest coolings (basket weave structure) (fig. 5b). A correct equiaxed structure (fig. 5c) is obtained due to rapid cooling from the beta range adapted to product size, followed by sufficient alpha + beta forging reduction, rapid cooling and recrystallization annealing. If cooling from beta is slowed, thicker alpha platelets will be obtained, and the same alpha + beta forging reduction will not be sufficient to provide an acceptable structure (fig. 5d).

4.3 - Effect of working speed

The excellent work of J.G. MALCOR and F. MONTHEILLET (15 to 19), who have studied the rheology of Ti-6Al-4V through torsion tests in the 800° to 1200° temperature ranges and for strain rates of 5.10⁻³ to 5.S⁻¹, shall be used as a basis. The study was performed with two initially different structures: the equiaxed structure and the acicular structure obtained by holding at 1050° and cooling in air.

For example, the curves of figure 6 show changes in flow stress σ , as a function of strain $\bar{\epsilon}$ for temperatures of 800 and 920° and the initial equiaxed (fig. 6a) or acicular (fig. 6b) structures. These curves underwent heating correction of up to 40°, as described in paragraph 3.3. In general, flow stress σ increases rapidly with strain $\bar{\epsilon}$, passes through a maximum σ_m , decreases (dynamic softening), then levels off.

It can be seen that the hot behavior of Ti-6Al-4V depends greatly on strain rate and temperature. Furthermore, at fixed temperature and strain rate, stress σ is systematically higher for acicular structures (with a tendency to localization) than for the initial equiaxed structure.

In the viscoplasticity formula: $\sigma = K \cdot \bar{\epsilon}^m$, coefficient m represents sensitivity to rate. The slope of the curves of figure 7 show that m is between 0.15 and 0.20 and that it increases lightly with temperature.

4.4 - Effect of strain temperature

The curves of figure 8 clearly illustrate the very marked influence of temperature and initial structure with highly different and typical behaviors of the biphasic alpha + beta and monophasic beta ranges.

At a given strain rate, stress σ decreases rapidly as temperature increases, up to a temperature slightly lower, by approximately 10 to 30°, than that of the beta transus, where curves $\sigma - T$ form an "elbow". This can be explained by the fact that immediately below transus temperature, primary alpha grains are few and behave a little like hard inclusions in a soft matrix; they play only a small role in strain, and overall flow stress is close to that of the beta phase (15-19).

Here again, at given temperature and strain rate, the initial acicular structure (figure 8b) shows a higher flow stress than the equiaxed initial structure (fig 8a). Above transus, stress depends only slightly on temperature.

The behavior law for Ti-6Al-4V alloy can be represented with adequate precision by a power law or by the SELLARS and TEGART empirical formula:

$$\bar{\epsilon} = A (sh \alpha \sigma)^P \cdot \exp \left(- \frac{Q}{RT} \right)$$

The structural evolution can be used to define the hot working mechanism of this alloy:

- a - in the alpha + beta biphasic range, dynamic recrystallization occurs only for low deformation rates ($\bar{\epsilon} < 10^{-2}$. S⁻¹) and is easier for the equiaxed structure (25, 26, 27). There is no dynamic recrystallization of alpha for deformed states at speeds corresponding to rolling (16, 17). These remarks are assembled on figure 9 (28). This can be interpreted as follows for a given strain rate: at the lowest temperatures (800 - 850°), thermal activation is insufficient to cause germination and growth of new grains; at higher temperatures, and around the beta transus, the proportion of alpha grains is low, and as "hard inclusions" are only slightly deformed by the environmental beta matrix, so that, for dynamic recrystallization, critical deformation is not reached (19).
- b - in the beta range, a process of the conventional "continuous recrystallization" type is observed, with appearance of new very small beta grains around the boundaries of the beta grains, then with higher deformation, inside the initial deformed grains.

4.5 - Effect of forging ratio in the alpha + beta range

It has been seen that deformation of the initial equiaxed structure is generally homogeneous. In the absence of dynamic recrystallization for strain rates of more than 10⁻¹, S⁻¹, the alpha grains elongate and recrystallize into equiaxed grains, during later recrystallization treatment.

From the conventional acicular structure (figure 5b), a low forging ratio leads to slightly different structure with the alpha needles beginning to orient themselves proportionally with temperature. Conversely, there is a much more marked tendency towards localization at low temperatures.

A true strain of 0.8 in the alpha + beta range must be reached, together with a temperature higher than 900°, to obtain a final equiaxed structure similar to that of figure 5c (9) after annealing. It has been seen that, for given temperature and strain rate, the initial acicular structure undergoes notable dynamic softening (6) in addition to a higher flow stress than the initial equiaxed structure. This dynamic softening is due, at least in part, to fragmentation of the alpha phase needles.

When conditions permit, this fragmentation of the alpha needles gives a fine structure liable to recrystallize into equiaxed grains during later treatment. These phenomena were fully studied by WEISS, FROES, EYLON and WELSCH (29,30) starting from two types of structure:

- fine alpha lamella obtained by water quenching at 1010° (length to thickness ratio 9.9), or
- thick lamella, obtained by furnace cooling at 50° per hour from 1010° (length to thickness ratio 6.2), forged at 955° and compression annealed at 925°. A true strain of 1.6 is required to orient the alpha lamella, to fragment these into small segments, and lead to an equiaxed structure which is much easier to obtain with the initial thin lamella than with initial thicker lamella (figure 10).

Two lamella fragmentation mechanisms are generally advanced, either with formation of sub-boundary or localized shearing across the alpha plates; then to complete the separation, the beta phase penetrates the alpha-alpha interfaces or the shear bands; this penetration becomes more difficult as platelet thickness increases. It should be noted that this penetration also depends on the rate of diffusion of elements Al and V.

Therefore, it can be seen that thermomechanical processing forms the most efficient method to modify the alpha + beta morphology. It should be remembered that a low length to thickness ratio of the alpha lamella (less than 3, for example) increases the yield strength, elongation and hot workability, while a high ratio favors fracture toughness, resistance to fatigue crack initiation and resistance to creep. Conversely, the ultimate tensile strength is not altered.

4.6 - Effect of cooling after alpha + beta deformation

After a sufficient amount of deformation, the alpha needles are broken and do not recrystallize, and natural cooling gives a microstructure with slight heredity. Recrystallization occurs during annealing at 940°. To avoid this supplementary treatment after forging, it is also possible to use very slow cooling, for example by replacing in the shut-down furnace, which recrystallizes the alpha phase.

4.7 - Effect of recrystallization annealing

Recrystallization of the alpha phase is therefore an important parameter. Figure 11 shows the results obtained for an amount of reduction $\bar{\epsilon} = 0.8$ at 950°, followed by annealing at different temperatures and for two post-annealing cooling modes (9, 10). The primordial effect of temperature can be seen.

4.8 - Thermomechanical processing in the beta phase

We have seen that hot transformation of Ti-6Al-4V alloy in the biphasic range leads to severe limitations related to poorer workability, absence of alpha phase dynamic recrystallization and a limited usable temperature range (800-975°). Conversely, in the beta range, the resistance to strain is much lower, and recrystallization of the beta phase is general and very fast, and accompanied by an equally rapid growth of the beta grain. It was interesting to see whether thermomechanical processing could be applied to this single-phase beta range.

Studies have shown that a hot working process in the beta range, applied with sufficient speed, could enable recrystallization to be avoided or minimized (3, 5, 7, 31). Beta recrystallization is effectively avoided on condition that:

- there is an interval between deformation runs of less than 10 to 15 seconds, and
- very fast quenching takes place with a return time to the alpha + beta range of less than 10 to 15 seconds.

Recrystallization treatment enables the structure to be globulized, and adequate ductility properties to be obtained. With periods of up to one minute, sufficiently fine recrystallized beta grains are obtained. Depending on product cross-section, a minimum forging for beta of 2 to 3 must be used.

This "fast beta" working technique therefore conserves the advantages of forging in the beta phase and of the acicular phase, while minimizing the fault of the latter: its low ductility. However, it is difficult to apply this to products of diameters of more than 50 mm, due to the low quenchability of 6-4. Conversely, this can be applied to thicker sheet (9).

5 - HOT WORKABILITY OF ALPHA AND NEAR-ALPHA ALLOYS

5.1 Hot transformation of alpha alloys is known to be difficult. Primarily, this is imputable to the narrowness of the alpha + beta range. Infact, for Ti-5Al-2.5Sn, there is only 60° between both

transus:

transus $\alpha \rightleftharpoons \alpha + \beta$ towards 980°

transus $\alpha + \beta \rightleftharpoons \beta$ towards 1040°

For this alloy, the curves of figure 12 show a very marked effect of strain rate on flow stress, together with a work hardening effect and a tendency towards localization of deformation for the highest speed.

For this alloy, the flow curves of figure 13 show a stress which varies strongly with temperature, and a rather sudden change in behavior in the range preceding the beta transus. Forgeability increases proportionally with the percentage beta phase formed as and when this transus is approached.

The same phenomena are observed in fast tensile strength tests, in which both ductility and strength are measured (figure 14). Also, this figure shows the effect of a small addition of iron, whose strong beta stabilizing action gives an interesting widening of the alpha + beta range, and thereby better workability.

It has been shown that the addition of a very small quantity of yttrium (25 ppm) improves rollability of Ti - 5 Al sheet by refining the structure and better distribution of the alpha platelet colonies (32).

In general, hot transformation of the Ti - 5 Al - 2.5 Sn alloy includes rough working of the ingot around 1150°, followed by rapid cooling and finishing forging with heating around 1010°, and forging reduction of approximately 3.

5.2 For near alpha alloys, the conditions are the same, with a restricted alpha + beta range. One of the methods consists in widening this range, as was used for the IMI 834 alloy (33). Sensitivity to strain rate seemed to be greater for the Ti - 6 Al - 5 Zr - 0.5 Mo alloy (685). It can be seen from figure 13 that the forgeability of this alloy is lower than that of Ti-5Al-2.5 Sn and of course, that of Ti-6Al-4V or unalloyed titanium. Here again, the fineness of the microstructure favors workability.

5.3 The near alpha alloy Ti - 6Al - 2Sn - 4Zr - 2Mo - 0.1 Si (6242 Si) is also reputed as delicate to form (21). The change in flow stress as a function of temperature and for various strain rates is similar to that of Ti-6Al-4V (figures 8 and 17a) and, once again, the acicular structure is stronger than the equiaxed structure.

Moreover, it is necessary not only to distinguish resistance to deformation of the material, but also its crackability. The difficulties with the 6242 Si alloy are related to a strong tendency to deformation localization during forming in the alpha + beta range. In fact, it is possible to observe the appearance of shear bands which can lead to the formation of cracks. This localization of the deformation has been the subject of numerous studies with, for example, the establishment of workability maps (21, 34, 35). Equational comparison of rheology and modelization with the effect of heating due to deformation have led to a concept of deformation efficiency in the form of processing maps for the initial acicular or equiaxed structures (36).

This shear band and crack phenomenon is aggravated by an initial acicular structure rather than an equiaxed structure, by decreasing temperatures, by increasing strain rates and also by superficial cooling of the metal in contact with the tool at a much lower temperature, illustrating the interest of isothermal forging. It is therefore recommended to perform finishing forging in alpha + beta at a high temperature near the beta transus (940-970°), with an initial equiaxed structure.

6 - HOT WORKABILITY OF BETA AND NEAR BETA ALLOYS

In terms of hot workability, the beta alloys offer several advantages, related, on the one hand, to the cubic beta structure, which is more ductile than the hexagonal alpha structure, and on the other hand, to the low transus temperatures (21, 37 to 41).

These alloys behave much differently than the previous alloys. For example, Ti-10V-2Fe-3Al (10-2-3) has a quasi monophasic beta state, and passage through transus is very slight at flow stress. Figure 15 gives an example of $\sigma / \dot{\epsilon}$ curves for this alloy at 650°. Here again, the importance of the strain rate can be observed.

On figure 16, it is possible to compare the effect of temperature on flow stress for this alloy and for Ti-15V-3Cr-3Al-3Sn (15.3). The curves are less sloped than for the alpha + beta alloys, and for alpha alloys and forgeability are not directly related to the idea of the beta transus. The stress level is, conversely, highly dependent on the content of alloying elements, 15.3 being harder than 10-2-3. This figure also highlights the wide forging temperature range for these alloys, enabling longer forging times before the appearance of cracks.

Lastly, for equal temperatures and strain rates, the flow stress of Ti-6Al-4V is systematically higher than that of 15.3 or 10.2.3 (with the exception of 15.3 for temperatures of more than 900).

Rough working of ingots is performed above the beta transus, as for the Ti-6Al-4V. Finishing forging can be made below the beta transus (for example 700-800° for 10.2.3) or on either side of this transus, for example 700-925° for 15.3). Metastable beta alloys require careful thermomechanical processing to obtain the final microstructure required, in particular as a function of the work-hardened or recrystallized state of the alloy, and in the latter case, as a function of grain size. It is more difficult to obtain a fine equiaxed beta grain structure than a mixed grain structure starting from the structure of the ingot as cast, which may contain elongated basaltic grains, with large equiaxed grains in the center. It has recently been shown (38,41) that a thermomechanical processing window existed leading to a fine equiaxed beta grain structure. This window is relatively wide for low alloyed metastable alloys, and for high deformations.

To sum up, the flow law and forgeability for alpha + beta and alpha alloys are clearly indicated by the beta transus transition, the suddenness of this transition being the source of many industrial difficulties. Conversely, the hot behavior of beta and near beta alloys is similar to that of a single-phase beta alloy. Figure 17a provides a general comparison σ / T for all these alloys. If these curves are referred to the beta transus temperature, the beta alloys are penalized and the flow stresses of 10.2.3 and, above all, 15.3 are higher (figure 17b).

7 - HOT TRANSFORMATION OF INGOTS AND SEMI-FINISHED PRODUCTS

7.1 - Forging ranges

We have seen that transformation in the beta range is relatively easy, due to:

- adequate forgeability of the beta phase
- very rapid dynamic recrystallization in this phase
- and much lower strain energies.

But the cooling which follows beta phase reduction is a determining factor. In fact, this leads to a thicker and thicker alpha lamellar structure and the appearance of an alpha boundary at the beta grain joints, as cooling slows down.

Therefore, heavy forging reduction in the alpha + beta range is necessary to break these lamella and to obtain an equiaxed structure after recrystallization treatment. We have also seen that, this transformation in the alpha beta range is much more difficult, and that it is characterized by:

- low upward limited temperature range due to low forging temperature range, limited at the top by the transus temperature which must not be crossed under any circumstances, and at the bottom by the appearance of shear bands and defects.
- much higher working energies, with a very marked effect of temperature, strain rate and initial structure.
- difficult alpha phase dynamic recrystallization in the alpha phase and limited to low strain rates.
- strain-related heating, which, in the case of localized deformation, can take the material beyond the transus temperature and cause important structural changes.

In this complex decor, the most simple industrial hot transformation range therefore consists of two successive steps: sequence 1, figure 4a)

- a - ingot rough-working in the beta range at a temperature of between 1000 and 1150° for Ti-6Al-4V alloy.
- b - finishing, with a forging reduction of at least 3 in the alpha + beta range (825°-975° range for Ti-6Al-4V). In fact, a reduction of 4 or 5 is required if it is desired to obtain a fine macrostructure and a homogeneous equiaxed microstructure.

The forging ranges can offer several options: for example, in sequence 2 (figure 4a), a beta recrystallization treatment is inserted with fast cooling between two forging operations in the alpha + beta phase. This beta phase recrystallization treatment, after alpha + beta phase prerefining, is highly efficient in improving homogeneity and finesse of the macro and microstructures.

Important heating energy savings can be made and production times can be decreased by reducing the four heating phases of the sequence 2 to only two heatings in the sequence 3; in fact, the deformed beta product is placed in a furnace at 950° for $\alpha + \beta$ forging, and beta recrystallization is made immediately after this forging (figure 4b).

It is possible to go even further by effecting the transus transient under deformation, so as to reduce the formation of grain boundary alpha at the beta grain boundaries (sequence 4).

7.2 - Modelization of forging operations

The conception of sequences of forging operations must respect the metallurgical constraints related to the product forged. In view of the complexity of the phenomena, and due to the assistance of computers, we are heading towards modelization of forging operations. In the United States, several methods are used to optimize the forging of a part. In particular, the ALPID model (Analysis of Large Plastic Incremental Deformation) should be mentioned, which, with the use of the finite element method, enables two-dimensional rigid-visco-plastic analysis for isothermal forming, and the ALPIDT version, coupled with a thermal transfer model to represent non-isothermic forging (44-45). This model calls for a load displacement relationship metal flow and variables at each point, such as distribution of temperatures, deformations and strain rates. A new, more complex version enables analysis of metal flow in all three directions.

In France, with the assistance of CEMEF and the Voreppe Research Center, we have developed a thermomechanical forging model for Ti-6Al-4V ingots. This model takes the following phenomena into account:

- convection and radiation around the product,
- plastic strain work
- contact with the stamp.

It enables calculation at all points of forged products, of:

- the product temperature map (an example is given in figure 18)
- deformation power and its local distribution
- deformation and strain rate.

This model is used to project forging sequences on the new CEZUS press installed at UGINE.

This forging press (figure 19) develops a force of 2500 tons, at a maximum rate of 150 strokes per minute and with a constant die stamp speed during the press strokes (maximum stamp speed 150 mm per second). It is integrated with its two manipulators which constantly measure product elongation and take this parameter into account in the next stroke advance.

7.3 - Modelization of rolling operations

Because we lack the time, we shall not discuss the particular aspects of hot rolling or extrusion here. Here again, modelization provides extremely precious information. Figure 20 gives a modelization example with the distribution of core, medium and surface temperatures for a continuous billet and wire hot rolling mill. The very pronounced effect of speed of passage through the last finishing stands can be seen, and the risk of passage into the beta range for an excessively high speed can also be observed.

8 - CONCLUSIONS

We have attempted to demonstrate the specific metallurgical characteristics of titanium alloys and reviewed the various hot working parameters for such alloys. These thermomechanical processes, which make use of recent knowledge of interactions between transformation ranges, structure and mechanical properties, form a particularly promising path, if it is desired to optimize the final utilization properties. At the moment, the mastery of these processes, the use of forging or die forging with preheated tools, and the arrival of modelization will enable new performance levels to be obtained for titanium alloy parts and products.

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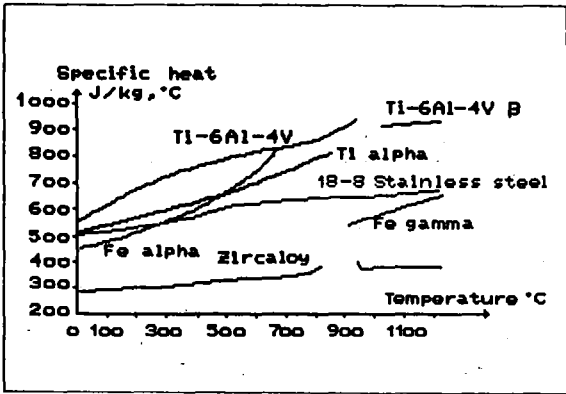


Fig. 1 - Specific heat of titanium and TA6V alloy

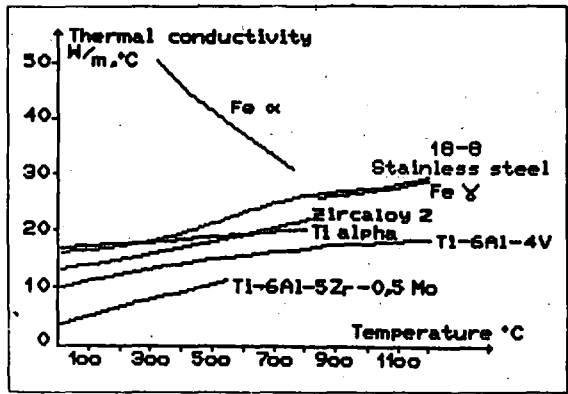


Fig. 2 - Thermal conductivity of titanium and TA6V alloy

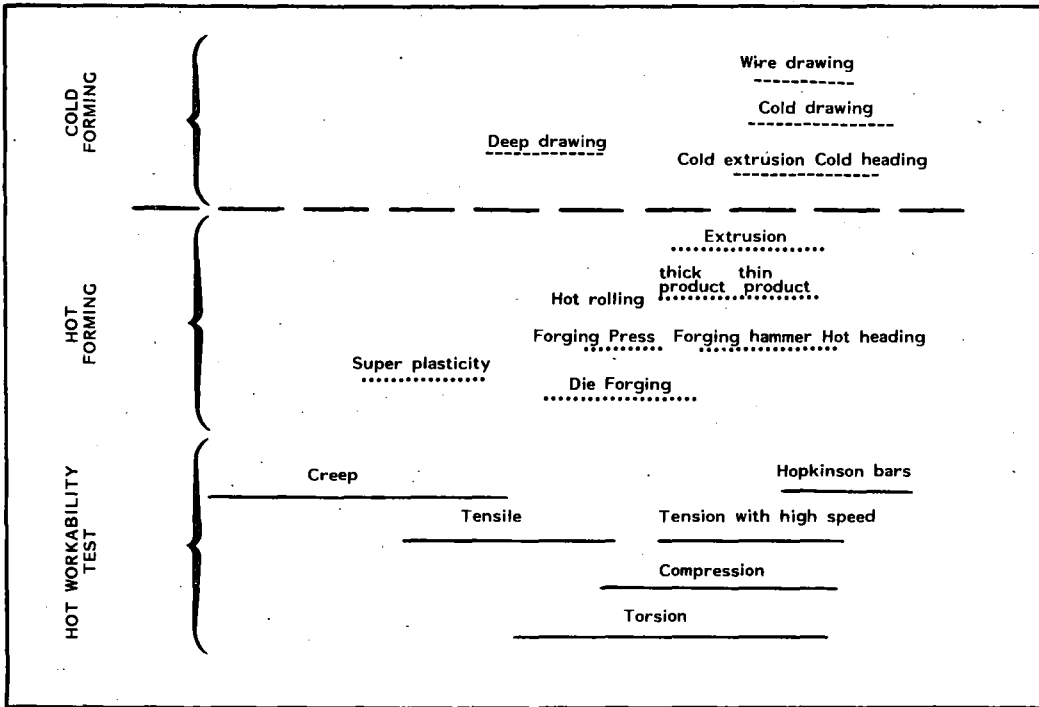


Fig. 3 - Strain rate for different working method

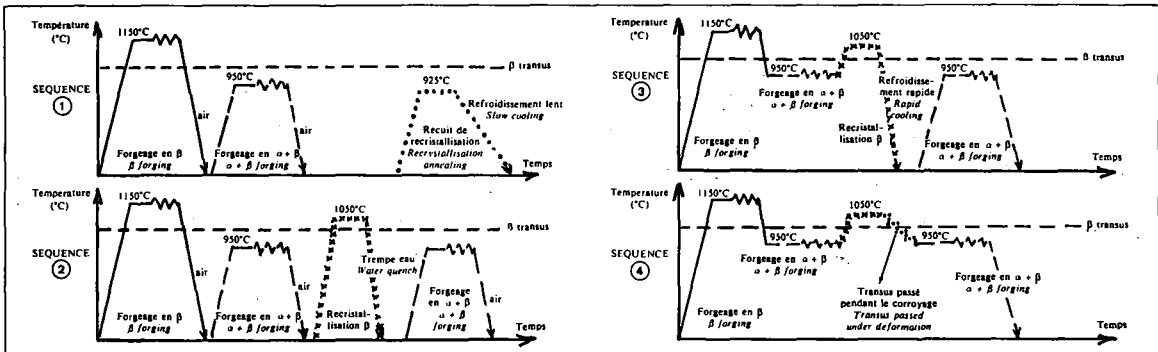


Fig. 4 - Examples of TA6V alloy forging operation sequences



Fig. 5a - Martensite structure α' (magnification 1 400)

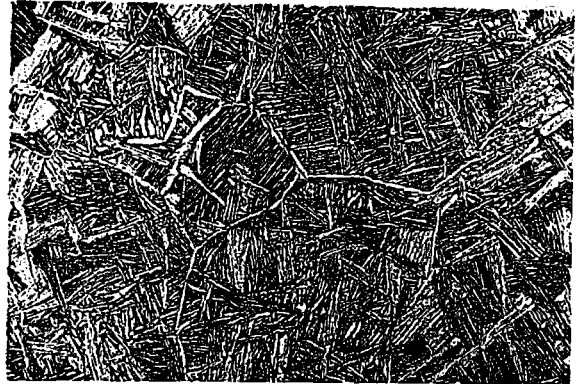


Fig. 5b - Basketweave structure (magnification 85)

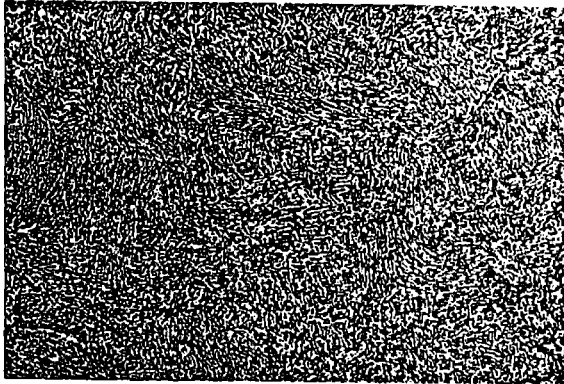


Fig. 5c - Equiaxed structure (x 85)

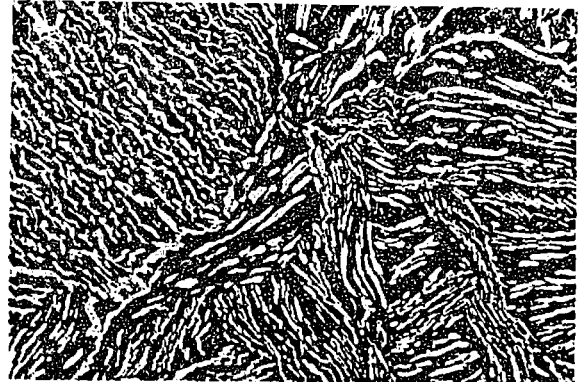


Fig. 5d - Insufficiently globulized intermediate structure (x 85)

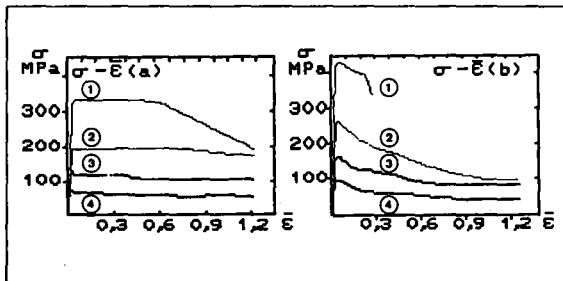


Fig. 6 - TA6V stress-strain curves. a) initial equiaxed structure ; b) lamellar structure (22).
 ⊙ $T = 800^{\circ}\text{C}$; $\dot{\epsilon} = 1,5 \text{ s}^{-1}$; ⊙ $T = 800^{\circ}\text{C}$; $\dot{\epsilon} = 5 \cdot 10^{-2} \text{ s}^{-1}$; ⊙ $T = 920^{\circ}\text{C}$; $\dot{\epsilon} = 1,5 \text{ s}^{-1}$; ⊙ $T = 920^{\circ}\text{C}$; $\dot{\epsilon} = 5 \cdot 10^{-2} \text{ s}^{-1}$.

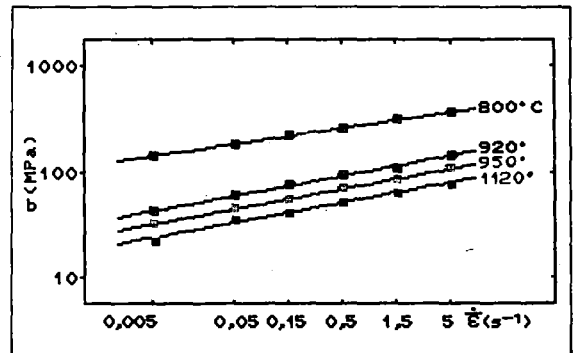


Fig. 7 - Variations in flow stress of TA6V with strain rate, with equiaxed initial structure (26).

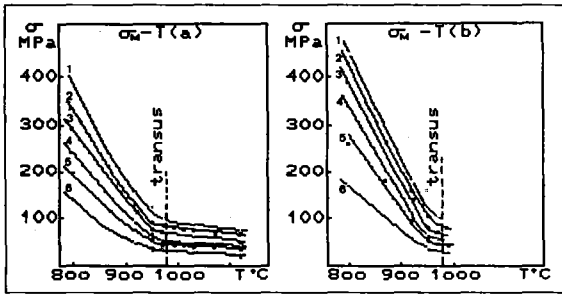


Fig. 8 - Flow stress curves of TA6V as a function of temperature for equiaxed initial structure (a) or lamellar (b), and for the following strain rates : 1: 5 s^{-1} ; 2: 1.5 s^{-1} ; 3: 0.55 s^{-1} ; 4: 0.15 s^{-1} ; 5: 5.10^{-2} s^{-1} ; 6: 5.10^{-3} s^{-1} [22].

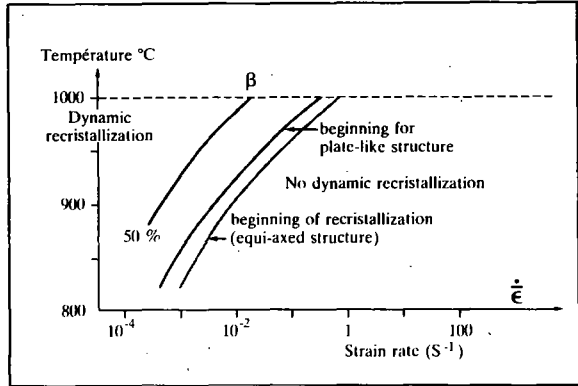


Fig. 9 - Dynamic recrystallization range of α phase of alloy TA6V in the temperature/strain rate diagram (33).

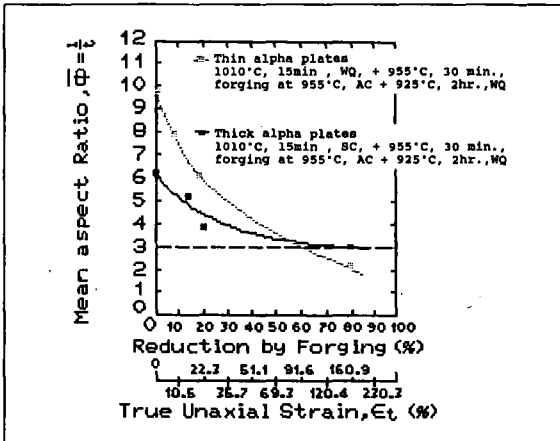


Fig.10 - Development of plate length/thickness ratio as a function of reduction by forging at 955°C for a thin (dotted line) or thick (plain line) plate initial structure.

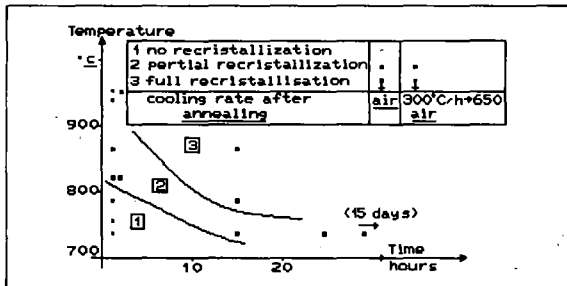


Fig.11 - Recrystallization diagram of α phase after strain of $\alpha = 0,8$ at 950°C (18).

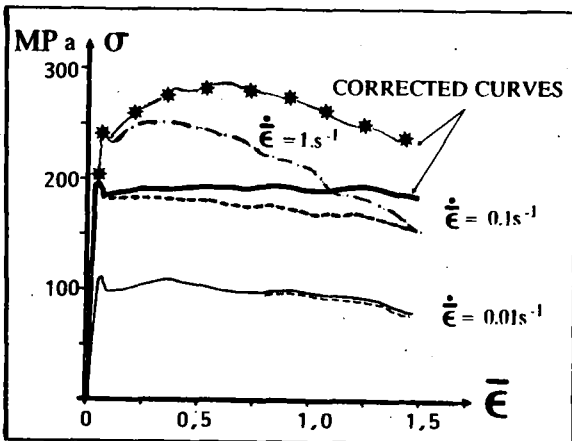


Fig.12 - Ti-5Al-2.5 Sn stress strain curves

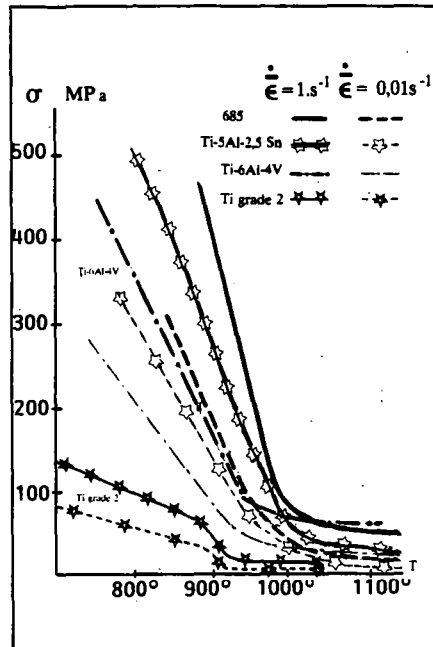


Fig.13 - Flow stress curves of alpha and near-alpha alloy

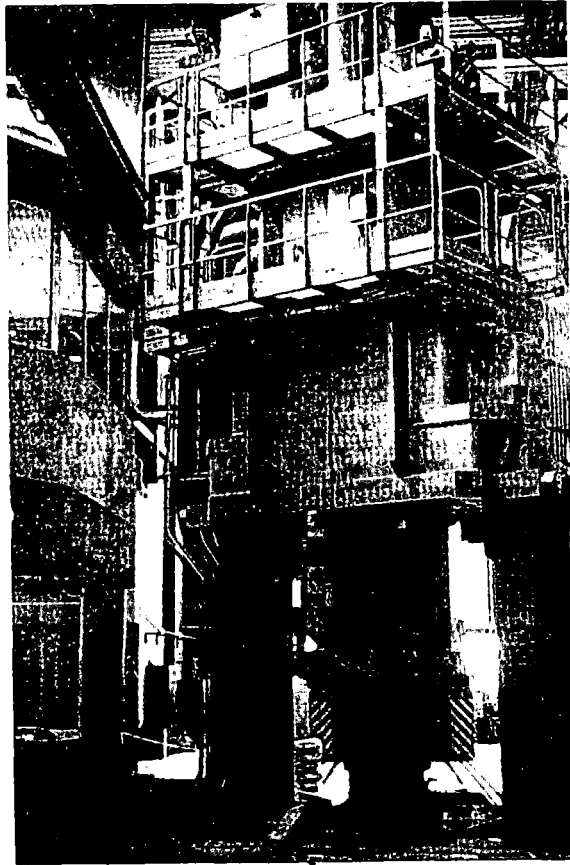


Fig.19 - The new Cezus 2 500 ton forging press.

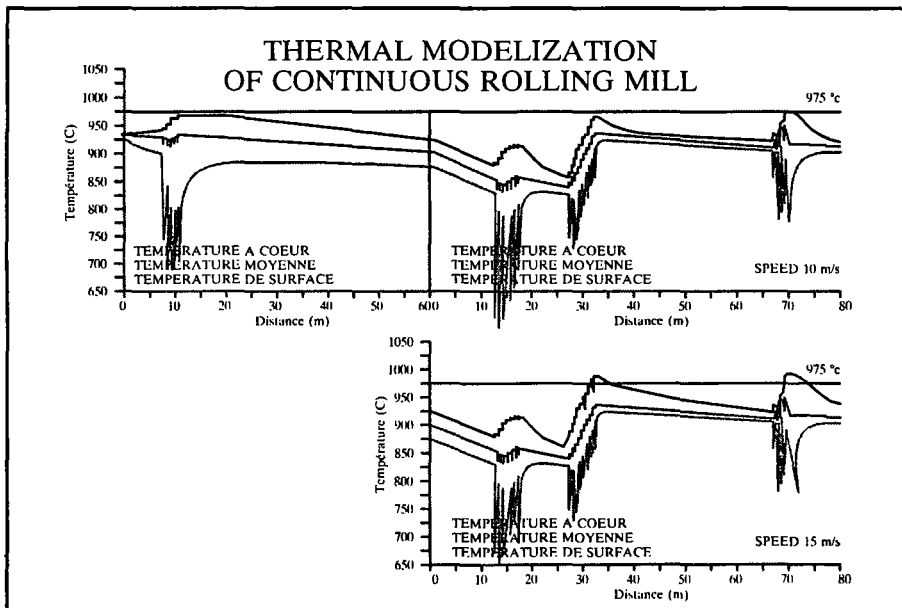


Figure 20

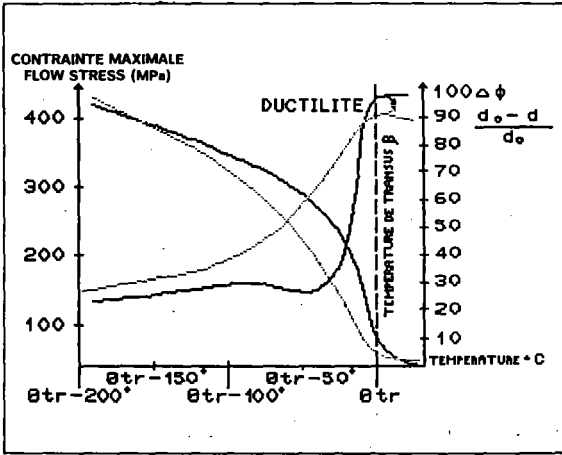


Fig.14 - Forgeability of alloy Ti-5Al-1.5 Sn with equiaxed initial structure and for two iron content levels : 0,1 % (bold) and 0,3% (38).

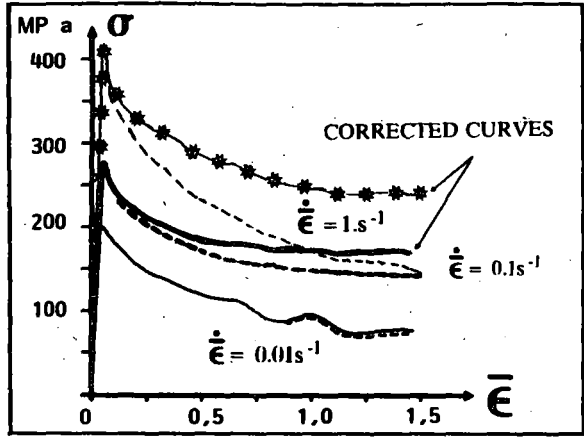


Fig.15 - Ti-10V-2 Fe-3 Al stress strain curves

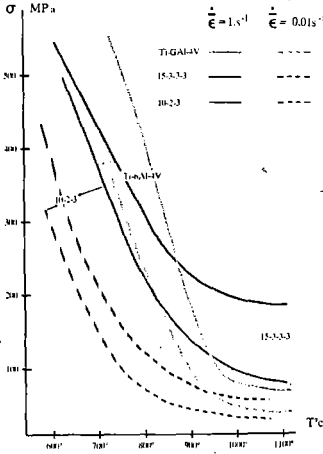


Figure 16 : Flow stress curves of beta and near beta alloys.

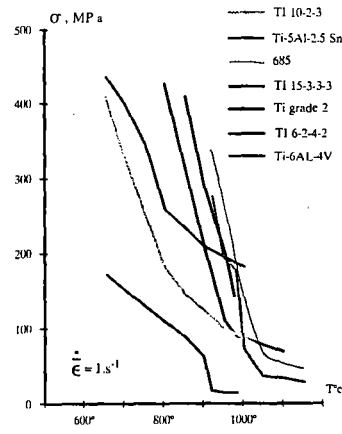


Figure 17a : Flow as a function of temperature : comparison between titanium alloys.

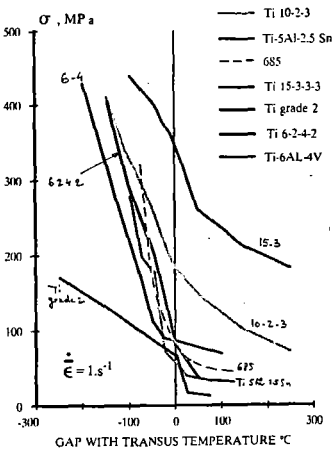


Figure 17b : General comparison of Titanium alloys : curves are referred to the beta transus temperature.

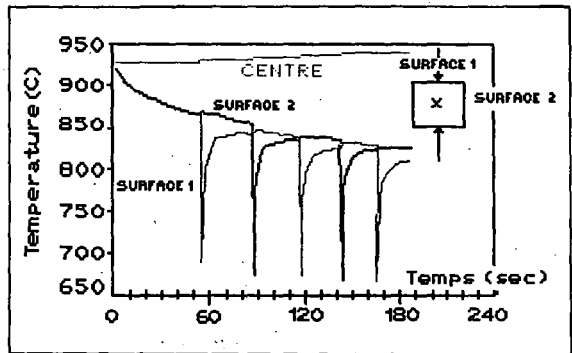


Fig.18 - Modelization of surface and core temperatures of a TA6V product as a function of forging runs.