

## Tailoring microstructures to improve thermomechanical behaviour of metallic alloys: Ti alloys for Aerospace applications

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### Abstract

*A more rational use of metallic materials for advanced applications (such as for example in aeronautics or fine mechanics) requires to generate the optimal microstructures through the control of the elaboration and fabrication processes.*

*In this context, the description of the critical parameters of the microstructure of the metallic materials, which influence the mechanical properties, is necessary. This step requires the knowledge of the thermally and thermomechanically activated phenomenons (phases transformation, recrystallisation, ...).*

*The interpretation and the synthesis of these observations are integrated within physical models which provide the elements necessary to the development of the physical or mathematical macroscopic model.*

*This paper will develop one example of the laboratory MMS researches (Special Metallic Materials) concerning the study of the physicochemical mechanisms controlling the microstructural genesis and the optimization of the mechanical properties.*

*In the case of nanostructured  $\alpha/\beta$  titanium alloys, bonds between mechanical properties and active microstructural elements will be presented.*

### 1. Introduction

The choice of the chemical composition, of the different parameters of material elaboration and of thermo-mechanical treatments of components has a great influence on the material microstructure in terms of: nature of the allied matrix (which leads to solid solution strengthening), nature and shape of the strengthening particles, grain size and shape, level of work hardening and recrystallisation ratios. These micro-structural parameters define the level of mechanical properties obtained. It is clear that, if improvements in the macroscopical

behaviour of materials are needed, it is important to develop the optimal microstructure leading to the desired properties by means of process control.

Today, modelling of micro-macro thermo-mechanical behaviour is more and more used due to the complexity of studied alloys and to the cost of the otherwise required experimentations for the study of materials and structures behaviour. This modelling allows the forward-looking calculation of the response and the mechanical properties of structural components. It allows also the development of new materials or the improvement of existing materials.

Moreover, this micro-macro relationship allows it to obtain the macroscopical mechanical behaviour through the microstructure description and the knowledge of the deformation damage mechanisms (fig. 1). Nevertheless, though the idea of establishing this micro-macro relationship is evident, in practice this approach necessitates numerous advanced analyses and a deep knowledge of physical phenomena.

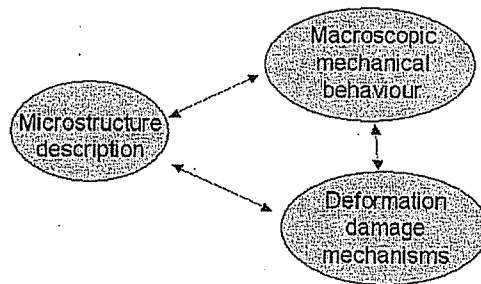


Figure 1: MICRO-MACRO relationship

The micro-macro modelling of thermo-mechanical behaviour necessitates the identification of base phenomena, the knowledge of their interactions and the transition to the macroscopical behaviour. In that spirit, the different steps of the modelling stand from the micro-structural characterisation to the study of thermo-mechanically activated phenomena (phase transformation, recrystallisation, ...).

The characterisation of the most important micro-structural parameters influencing mechanical properties leads to a fine qualitative description of the involved phenomena.

This step will allow establishing and using materials behaviour laws which necessitate parameters quantification. This quantification is not necessarily the simplest one. These materials laws are then incorporated in FE modelisation. The last step is then the general macroscopical validation.

## 2. Context

This article will be dedicated to micro-structural studies and to the relation between microstructure and mechanical properties in order to establish physical models.

These studies give also some parameters, as for instance thermo-physical properties, that are mandating for the modelling.

This approach will be illustrated in one study carried out at the moment in the laboratory of Metallic Materials Science at the University of Liège. It concerns Titanium alloys for aerospace applications and specifically mechanical properties optimization by the control of micro-structures in  $\beta$ -metastable alloys.

## 3. Ti alloys for aerospace applications: mechanical properties optimization of new $\beta$ -metastable alloys

The studied component is a low-pressure compressor shaft. The targeted properties are: a high strength ( $> 1100$  MPa) and an extended fatigue life (LCF  $10^7$  CYCLES UNDER 650 MPa at 150°C).

The high stresses needed are due to the fact that, when a fan is accidentally released, the casing must contain the scraps and the shaft must hold the blow and the unbalance.

Nowadays, steel is used by European motorists for this application, but, due to weight matters, high strength titanium alloys could be used. They are already used in the US for this type of component.

The choice of Ti alloys is justified by the properties of these alloys as can be showed in an Ashby diagram where density is plotted in function of endurance limit for example (fig. 2).

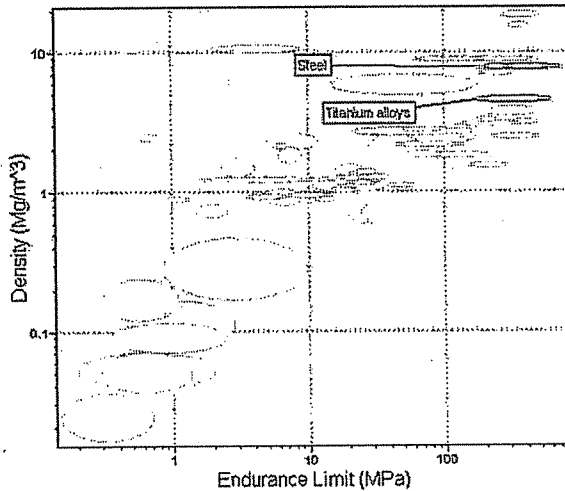


Figure 2: Ashby diagram of density in function of endurance limit

### 3.1. Ti alloys: uses and fundamental aspects

Due to this good combination of mechanical properties, corrosion resistance and density, the titanium alloys are used in various applications such as biomedical application, sport equipment, etc.... But it is in the aeronautical domain that the use of these alloys is increasing, the main advantage being their low density. This material can also develop various microstructures and then various behaviours due to the existence of this allotropic phase transformation.

Pure titanium presents a phase transformation at 882°C between a high T° stable BCC structure and a low temperature HCP phase (fig. 3). The presence of alloying elements modifies this transformation temperature. The  $\alpha$ -stabilizing elements increase the transition temperature. The effect of these elements is generally expressed in terms of the parameter Aluminium equivalent (Al being the most important  $\alpha$ -stabilizing element). The  $\beta$ -stabilizing elements lower this temperature. Their effects are generally expressed in terms of Molybdenum equivalent parameter (Mo being the most important  $\beta$ -stabilizing element) (fig. 4).

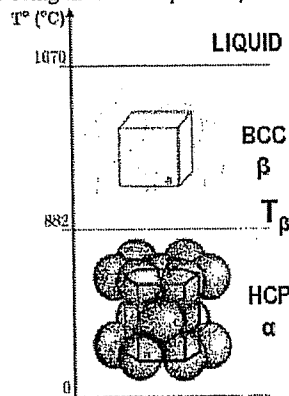


Figure 3: Phase transformation of pure titanium

<b><math>\alpha</math>-stabilizing elements: <math>\Delta T_{\beta}</math></b> Al equivalent = $Al + Sn/3 + Zr/6 + 10(O_2 + N_2 + H_2)$	<b><math>\beta</math>-stabilizing elements: <math>\Delta T_{\beta}</math></b> Mo equivalent = $Mo + 2V/3 + Nb/3 + 3(Fe + Cr)$
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Figure 4: Aluminium and Molybdenum equivalents parameters in Titanium Alloys

As a consequence and depending on the alloying elements, the  $\alpha$  or the  $\beta$  phase will be enhanced, thus leading to three alloy families:  $\alpha$  alloys with a unique  $\alpha$  phase and a lack of response to thermal treatment,  $\alpha + \beta$  metastable alloys, which are the most used, and  $\beta$  metastable alloys (fig. 5).

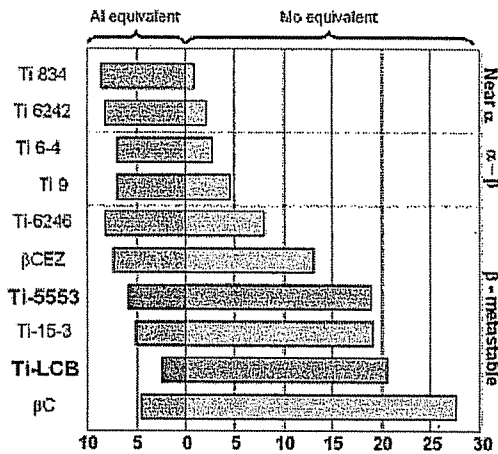


Figure 5: The three Ti alloy families depending on the alloying elements

The best known alloy is the TA6V alloy, which is a  $\alpha + \beta$  and is still used in motors or structural applications where the service temperature is about 350°C.

In motors, the alloys are used at increasingly high temperature and stresses, and optimizations are obtained on existing alloys such as  $\alpha$  or  $\alpha + \beta$ .

The  $\beta$  alloys with high mechanical characteristics are more and more used for parts like landing gears.

### 3.2. $\beta$ - Ti alloys

These  $\beta$  alloys possess enough  $\beta$  stabilizing elements to avoid the  $\beta$  phase transformation in  $\alpha$  martensite during quenching as shown in fig. 6.

The  $M_s$  point of the beginning of  $\alpha$  martensitic transformation is positioned at a lower temperature than the room temperature. It is then possible to keep the BCC  $\beta$  phase, which is more ductile in a metastable state during the deformation, before developing at a high temperature an  $\alpha + \beta$  structure nearly at equilibrium thanks to an adequate ageing. The combination of these two advantages, easy shaping at intermediate temperature and strong mechanical characteristics, leads to the increasing use of these  $\beta$  metastable alloys.

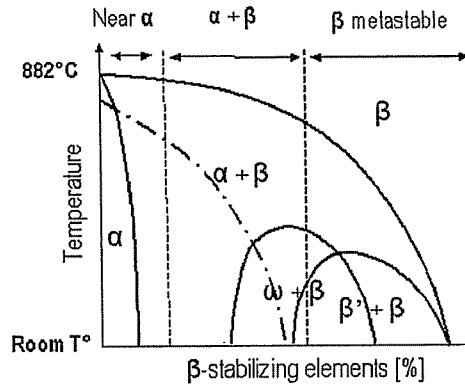


Figure 6: Phase domain in function of  $\beta$ -stabilizing elements and temperature

Several phase transformations can arise in the  $\beta$  phase. This allows a great liberty to the scientist or the engineer to tailor the microstructure in order to optimize the properties. Nevertheless, a lack of knowledge could lead to micro-structural instabilities which are detrimental to the mechanical properties. The control of thermal treatment in  $\beta$  metastable alloys allows it to obtain strong mechanical properties by the control of the phase transformation.

Two ways are possible to obtain the decomposition of  $\beta$  metastable phase.

At a high temperature, the nucleation of acicular  $\alpha$  precipitates (laths) is possible. At a low temperature, the  $\alpha$  decomposition is difficult and other decomposition products such as hexagonal  $\omega$ , which is metastable, could appear. The interest of this method is to form nanometric  $\alpha$  which possesses important strengthening effect.

**The objectives to be reached at microscopical level are:** obtaining a fine and homogeneous  $\alpha$  distribution in  $\beta$  metastable phase, avoiding continuous big  $\alpha$  particles on grain boundaries that could become weaker and favour cracks propagation, avoiding  $\omega$  weakening phase and obtaining fine grain size.

### 3.3. Results of Ti-555 and Ti-LCB studies

Two different alloys were studied. Their chemical composition is reported in table 1. Ti-LCB is a Timet's low cost solution intended to unlock new market. Ti-555 is an improvement of an old VT22 alloy intended for high strength forgings (such as large aircraft landing gears).

Table 1: Chemical composition of the Ti-555 alloy and Ti-LCB alloys

	Ti	Al	Mo	V	Cr	Fe
<b>Ti-555</b>	Bal.	5	5	5	3	0.3
<b>Ti-LCB</b>	Bal.	1.5	6.8	-	-	4.5

The industrial treatment on Ti-555 is a two steps heat treatment leading to a bimodal structure. The thermal treatment consists in a solutionizing treatment above  $T_p$  followed by a first ageing at 830°C and a second ageing at 620°C. The microstructure obtained is illustrated in fig. 7. It consists in  $\alpha$  particles embedded in a  $\beta$  matrix, in which an  $\alpha$  acicular is precipitated. The mechanical properties are then obtained: a strength of 1300 MPa, a micro-hardness of 4,6 GPa and an elongation at fracture of 3 %.

The aim of this study is to increase the properties of the alloy by tailoring the decomposition of the  $\beta$  metastable phase to reach the objectives highlighted under point 3.2.

Ti-555

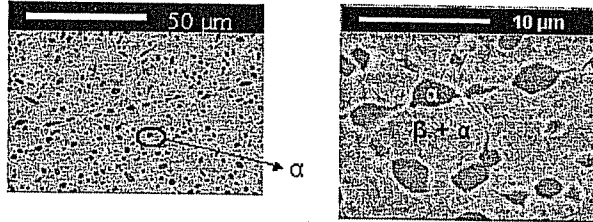


Figure 7: Bimodal microstructure obtained after industrial thermal treatment

The direct ageing from the solutionizing temperature (above  $T_{\beta}$ ) called method 1 leads to  $\alpha$  precipitation whose morphology and volume fraction depends on the ageing temperature.

Precipitation of an  $\alpha$  in the form of laths arises from the grain boundary or inside the grains. Their quantity increases as temperature is decreasing, as illustrated in fig. 8 a). The  $\beta$  matrix is completely transformed at 500°C is a mixture of  $\alpha$  precipitates in a  $\beta$  matrix. A very fine precipitation of  $\alpha$  particles occurs for ageing under 400°C.

Combining two different ageing temperatures can generate the bimodal structure used in industry up to now, with large precipitates of primary  $\alpha$  embedded in a  $\beta$  matrix strengthened by a secondary precipitation of fine  $\alpha$  laths (fig. 7), whose properties were defined above.

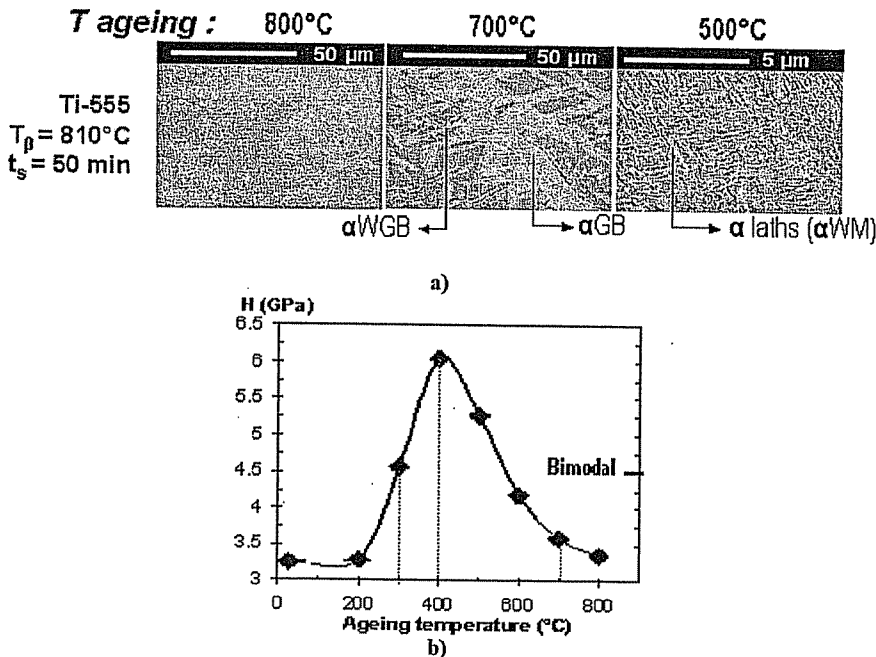


Figure 8: a) Increase of  $\alpha$  precipitation as ageing temperature is decreasing. b) Micro-hardness in function of ageing temperature in Ti 555

This bimodal structure is used to minimize the loss of ductility due to the presence of fine secondary  $\alpha$ , thanks to the presence of big  $\alpha$  grains, while keeping a high strength. But the mechanical properties are not yet sufficient for the requirements of the application (landing gear).

Attempts are made to use the direct ageing to increase the properties by decreasing the ageing temperature. As shown in fig. 8 b), the micro-hardness increases first with a maximum for direct ageing at 400°C and then decreases monotonously. This is related to the state of  $\alpha$  precipitations. The big precipitates obtained at 700°C lead to low hardening. The increase in thinness of precipitates is correlated with an increase in hardness. For ageing at a temperature lower than 400°C, the thermal activation energy is not sufficient to reach the complete  $\alpha$  precipitation. The optimal hardness is obtained at 400°C and is larger than the hardness of the bimodal structure (4,6 GPa). Fig. 9 sums up the tensile properties of this alloy Ti 555, after ageing at a different temperature between 300 and 800°C. The tests confirm the high properties that can be obtained (1500 MPa for ageing at 500°C). However the ductility becomes problematic for low ageing temperature for which the hardest samples show a brittle behaviour.

It is assumed that the presence of  $\omega_{\text{ath}}$  phase during ageing is responsible for this weakening. The presence of very small particles of  $\omega_{\text{ath}}$  has been proved by fine microscopical examination (using transmission microscope) as shown in fig. 10. The size of these particles is about 20 Å.

### Tensile tests

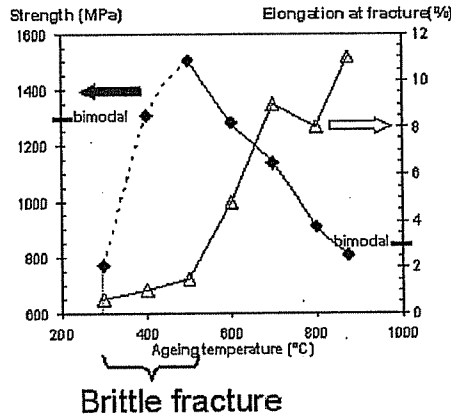


Figure 9: Tensile properties of Ti-555 after ageing [4]

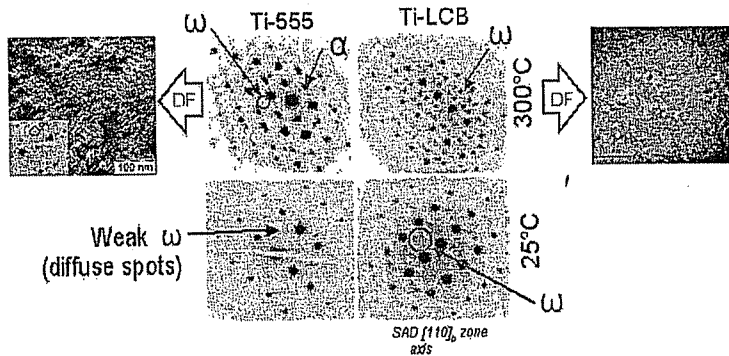


Figure 10: Microscopical examination (using TEM) of Ti-555 [4]

A way to avoid this  $\omega$  weakening would be to allow the transformation of  $\omega$  precipitation into other less detrimental phases. This could be realised by using the method 2 which corresponds to ageing after quenching. The direct ageing called method 1 leads to bathes of  $\alpha$  as illustrated in fig. 11. This transformation appears at a temperature around 600°C during the cooling step from the temperature of  $\beta$  transus  $T_{\beta}$  as shown in DSC curves on cooling as illustrated in fig. 12.

Ageing after quenching, called method 2, leads to more complicated transformations and could be used to develop an advanced microstructure with improved properties using  $\omega$  as precursor.

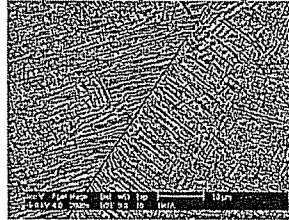


Figure 11: Lathes of  $\alpha$  after direct ageing (method 1)

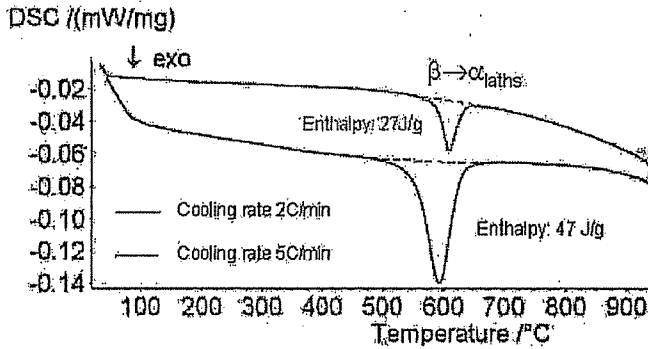
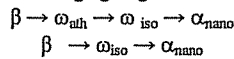


Figure 12: DSC curves on the cooling step during direct ageing (method 1)

After quenching,  $\beta$  metastable is retained and during ageing the following transformations occur



leading, in the end, to fine particles of  $\alpha_{nano}$ . This is illustrated in fig. 13 showing the DSC curves on the heating step (after quenching).

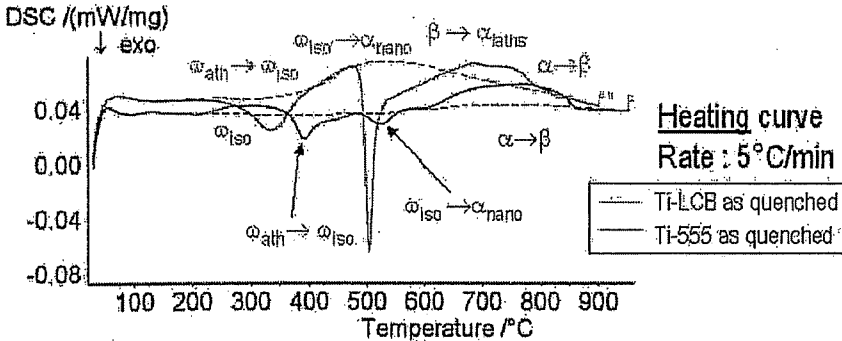


Figure 13: DSC curves on the heating step during ageing after quench (method 2)



The  $\omega_{iso}$  phase precipitates generally during heat treatments between 200°C and 500°C. However, its growing mechanism is not well known at present and need more study but can generate a very thin  $\alpha$  phase that is interesting with regards to mechanical properties. This nanoscale  $\alpha$  phase precipitation generates a pronounced increase in hardness.

### 3.4. Discussion

$\beta$ -Ti alloys show great perspectives in structural application where their mechanical properties can compensate their cost.

A control of the microstructure could optimize their mechanical properties. Nevertheless, these  $\beta$  alloys such as Ti 555 show a great variety of microstructures resulting from process variation that could lead to variable resistance and ductility levels.

Although they have a high level of alloying elements, they keep a low density together with a unique combination of properties. Stability at a low temperature and possibility to ageing allow it to form precipitates whose morphology and shape range on several orders of size. But the numerous phase transformations arising within the  $\beta$  phase mean both a strength and a weakness. They give the engineer a great liberty but a lack of knowledge or of control could lead to microstructural instabilities which are detrimental to the mechanical properties.

The strengthening mechanisms in  $\beta$  metastable alloys are due to the precipitation of  $\alpha$  phase. But although the  $\alpha$  precipitation could lead to high strength levels, the price to be paid in term of loss of ductility is sometimes high. This is why complex thermo-mechanical treatments combining mechanical and thermal activations are necessary to increase the properties.

The definition of these complex thermo-mechanical treatments is based on a good understanding of the physical behaviour of these alloys.

### 4. Conclusions

Nowadays, in order to reach high performance of materials, it is important to tailor microstructure for the optimization of the thermo-mechanical behaviour. Due to the complexity of existing alloys, this task requires a lot of efforts.

Multidisciplinary aspects have to be studied. Moreover, a good knowledge of the different phenomenons arising inside the materials is important to define and reach this purpose and to make the link with the modelling possible.

For example we showed in the  $\beta$ -Ti alloy studies that the high level of properties is due to several strengthening mechanisms: the solid solution atoms, the grain size (Hall Petch), the precipitation hardening (Orowan). Finally, to tailor the microstructure a deep understanding of phase transformations, subsequent microstructure transformations and effect on mechanical properties is needed.

These informations must then be integrated into micro models with FE representative cells using crystalline plasticity theory and damage models. This will allow the prediction of the effects of main microstructural parameters on damage. The last step will consist of validation of constitutive model for mechanical behaviour (such as fatigue) and of validation on real parts.

This aim has to be reached thanks to a national and an international collaboration.

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