SPECIFIC REQUIREMENTS FOR CRYOGENIC USE OF MATERIALS FOR SPACE ENGINES

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ABSTRACT

Enhanced performance characteristics and the quest for ever-increasing reliability against a highly competitive technical and economic background are the motives behind the development of ARIANE 5. As project managers for the European Space Agency programme, the French National Space Research Centre (CNES)(1) chose the Société Européenne de Propulsion (SEP) as the prime contractorfor engine development.

As with the 3rd stage of ARIANE 4, the main stage of ARIANE 5 makes use of cryogenic propulsion. To upgrade from 6 tons of vacuum thrust to 112 tons, however, and from 11 tons of propellant to 156 tons respectively, creates new problems of architecture, design and choice of technologies, materials and processes.

One of the major difficulties to be overcome is the engineering of high-performance structures capable of withstanding severe constraints of stress under extreme temperature conditions (4 K to 3,500 K) and in highly specific environments (hydrogen, oxygen).

Cryogenic propellants will be systematically used for the future systems of propulsion because of the specific impulse (ISP > 450 s) they enable vehicles to reach. New materials and technologies will have to be implemented in order to produce the engines and meet even more demanding requirements. The same applies to the tanks, the structural indices of which will have to be improved.

To meet these challenges the Société Européenne de Propulsion (S.E.P.), within the framework of cryogenic engine development, has acquired the know-how and implemented the means enabling the study, selection and qualification of the materials under operational conditions. The research is based on in-house test facilities, on a network of French and European and CIS partners for the future development of the related materials and processes.

Several examples are presented below with regard to the cryogenic pumps and the combustion chambers.

1. - INTRODUCTION

Enhanced performance characteristics and the quest for ever-increasing reliability against a highly competitive technical and economic background are the motives behind the development of ARIANE 5, whose first flight is programmed for year-end 1995, and whose operational use is scheduled to the year 2010.

The above combination of materials, implementation methods and the related control processes must enable parts to be obtained which are more reliable at lower costs.

One of the major difficulties to be overcome is the engineering of high-performance structures capable of withstanding severe constraints of stress under extreme temperature conditions (4 K to 3,500 K) and in highly specific environments.

In cryogenics, the mechanical and physical properties of materials, however, can be considerably affected by the temperature (increasing their tensile strength but deacreasing their ductility and KIC). Furthermore, an absolute prerequisite for the use of materials in cryogenics is full comprehension of the metallurgical relations, working, microstructures and characteristics after working, welding, brazing, quenching and tempering, and metal finishing treatment, if we wish to check their reproducibility and performance characteristics in their area of use.
The compatibility of the materials with the propellants used and tribological aspects are another important factors to take into consideration.

(1) Centre National d'Etudes Spatiales Français

It is against this background that the Société Européenne de Propulsion (S.E.P.), is working to acquire the requisite know-how, and have implemented the facilities enabling the study, selection and qualification of the materials under operational conditions.

After a brief overview of the development in materials properties at low temperatures, and a description of the means implemented at the SEP in this presentation we have chosen to examine the following in closer detail:

1) The engine pump rotors: requirements and problems linked high centrifugal stress, and to tribological aspects.
2) The combustion chamber developed by DASA (Germany), under project management by the Société Européenne de Propulsion (SEP) : to extremely high internal temperatures and heat flux, and regenerative cooling with hydrogen.

2 - GENERAL PROPERTIES OF MATERIALS IN A CRYOGENIC ENVIRONMENT

In general terms, mechanical properties, Tensile ($Re_{0.2}$, Rm, E) and fatigue limits (σD)increase when temperature decreases (either continually, or reaching a maximum at a given temperature), while the aspect ratio A % and the reduction of area % tend to decrease.

In low cycle fatigue (LCF) conditions, if we restrict ourselves to the scope of small plastic deformations, the material has a tendency to consolidate more easily than at ambient temperature conditions.

The crack growth rate between the ambient temperature and low temperatures increases, and the fracture toughness of certain materials (K1C) diminish as does the size of the plastic area at the bottom of the crack. In this case, the size of admissible defects is therefore smaller.

One of the major problems encountered in cryogenic engines results from very high temperature gradients (propellants at 20 K and 90 K, gases expelled at several thousand degrees), which has a result of dilatation and thermal conductivity create quite considerable mechanical stresses.

Oxygen compatibility has to be taken into account in the choice of materials in order to avoid ignition.

Hydrogen under pressure can also severely embrittle the alloys, either as a result of the formation of hydrides, or by internal diffusion. In general, embrittlement is maximum at ambient or high temperatures. When the temperature decreases embrittlement attenuates to become nonexistent below 200 K.

Tribological aspect is very important and has to be taken into account in the beginning of the design.
The tribological properties of a coupling are a function of the hardness and the coefficient of friction (Achard's Law). Since the cryogenic environment prohibits the use of any liquid lubricant, we therefore have to solve the problem of boundary friction.

3 PRESENTATION OF CHARACTERIZATION MEANS FOR CRYOGENIC TESTING

3.1 - Mechanical testing in cryogenic environment

The test facilities are located at the Société Européenne de Propulsion (SEP) at Vernon. The test devices enable coverage of load ranges from 5 kN to 250 kN, and temperature ranges from 4 K to 300 K. The facilities also comprise automation systems for cooling and temperature control.

3.2 - Compatibility tests

These tests are carried out at the L'Air Liquide technical centre at Blanc Mesnil.

With regard to hydrogen, mechanical testing under hydrogen pressure enables material sensitivity to be determined by analysing developments in their mechanical characteristics (tensile tests, da/dN, disk fatigue or fracture under pressure). (B attelle, Le Creusot and Volvo flymotor)

3.3 - Tribological tests

The test facilities are located at the Higher Institute for Mechanical Construction and Materials(2) at St Ouen, at the L'Air Liquide plant in Sassenage, and at the Technology University in Liège under the supervision of FN Moteurs (Belgium).

4 - USE CONDITIONS AND DEVELOPMENT OF MATERIALS UNDER CRYOGENIC CONDITIONS

The principal objectives of all the research carried out so far are as follows:

1 - To statistically guarantee material characteristics.
2 - To guarantee process reproducibility, in particular with regard to metal working and manufacturing processes, and to ensure the reliability of the related inspection means.
3 - To obtain a balanced implementation process/requirement relation by fully understanding the metallurgical phenomena governing the properties of the materials employed.

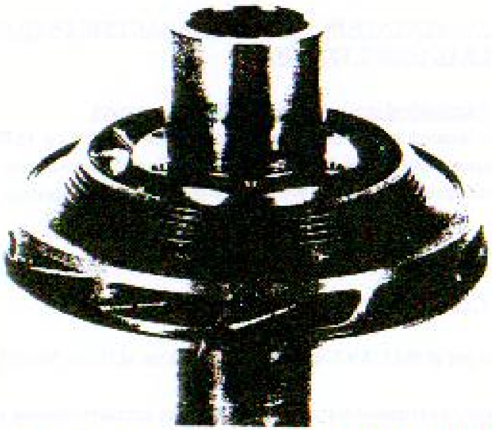
4.1 - Alloys for hydrogen pump rotors

4.1.1 - Expressed requirements

When considering the impeller and inductors of centrifugal pumps we are confronted with the problem of materials designed for parts rotating at high speeds. These parts are generally complex in shape in order to optimize their hydraulic performance and avoid cavitation, albeit within the limits of manufacturing processes and the accessibility of tooling.

(2) Institut Supérieur des Matériaux et de la Construction Mécanique

FIGURE 1 - VULCAIN IMPELLER



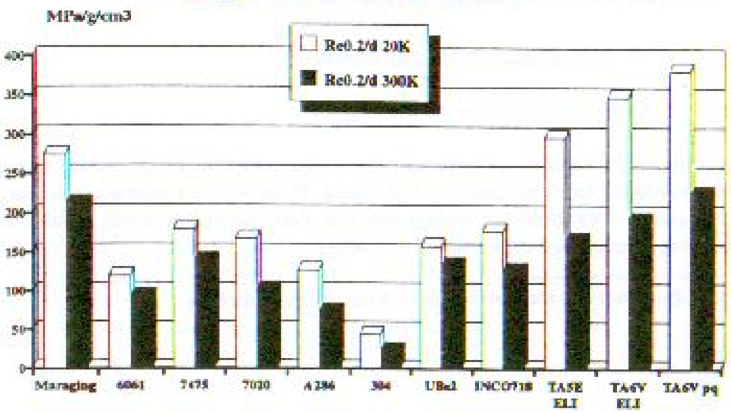
The specific requirements at the operating temperature (20 K) are therefore as follows:

a specific yield limit ($Re_{0.2}$/density) as high as possible, the highest yield limit possible for the chosen material , sufficient ductility while avoiding any ductile-brittle transition temperature, the highest KIC possible in order to avoid any cracking off as a result of cleavage fracture in the event whereby a defect existed beforehand or develops in the part during operation, a limited crack growth rate, the highest fatigue limit possible, given that the number of cycles to which the material is subject reaches figures ranging between 10^7 and 10^8 cycles for a burn time of approximately 6,000 s (in the case of the VULCAIN engine for example), finally, compatibility with the propellants, in particular in the case of use with oxygen where the risk of flammability is high in the event of impact or friction.

4.1.2 - Choice of TA6V alloy

If we consider the possible alloys solely in terms of their specific tensile properties (in relation to density) (see fig.3), it is clear that the choice of a titanium alloy is the wisest.

FIGURE 2
COMPARISON OF DIFFERENT MATERIALS POSSIBLE
$Re_{0.2}$/density at 300 K and 20 K



It should be noted that titanium alloys have an added interest in relation to other (aluminium- or nickel-based) alloys, in that its mechanical properties (RM, $Re_{0.2}$) double between 300 K and 20 K.

Precautions have to be taken in its use,however, since its ductility at 20 K can drop considerably to very low values (A % -1 to 3), and the KIC (30 MPa $\sqrt{m}$), depending on the structure obtained, the method of working, the level of interstitial elements, and finally the thermomechanical and thermal treatment carried out.

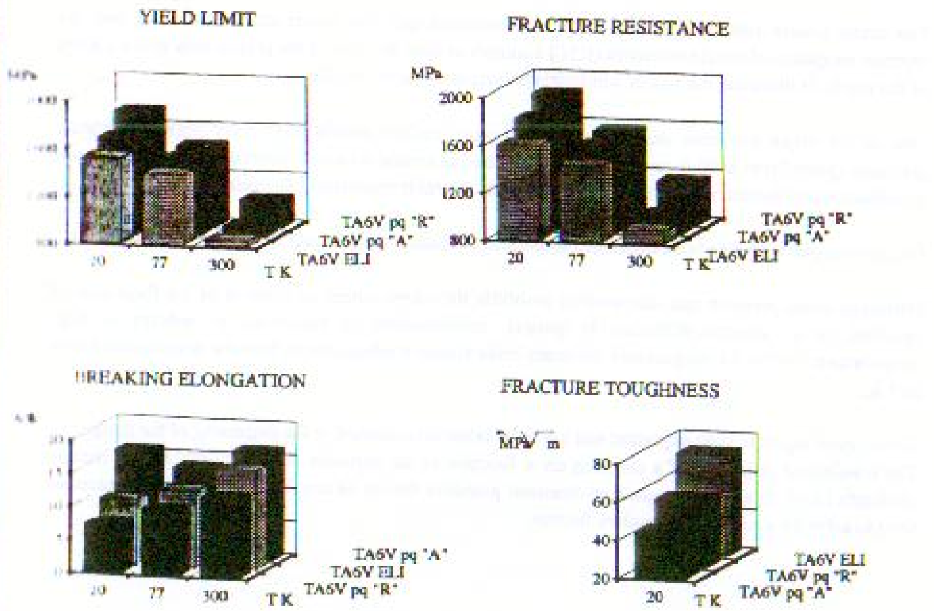
In order to further guarantee cold ductility we have selected a grade with limited oxygen, iron and hydrogen contents, the TA6V ELI (0_2 < 1300 ppm).

The consequence, however, is a considerable reduction in the $Re_{0.2}$, Rm and fatigue limit properties in relation to the TA6V PQ alloy, but this is the ransom to be paid for seeking the optimum performance/reliability ratio.

Research has therefore been carried out, analysing the evolution in the properties of the TA6V PQ alloy while keeping the oxygen rate to a standard level (1500 ppm to 2000 ppm) but developing the structure of the alloy, and comparing the influence on its properties in traction (A %, $Re_{0.2}$, RM), the KIC, the fatigue properties and notch sensitivity.

FIGURE 3
EVOLUTION IN TA6V PROPERTIES AS A FUNCTION OF TREATMENT, COMPARISON WITH TA6V ELI

TREATMENT "R": ENHANCES RESISTANCE AT 20K
TREATMENT "A": ENHANCES RESISTANCE AT 20K



The research, which is currently in progress would enable to perform the design based on a grade of TA6V PQ (non-ELI), of a range of thermomechanical and thermal treatment enabling the following (structure type $\alpha + \beta$):

a) either resulting in a very high level of mechanical characteristics at 20 K in tensile (20% higher than the optimized ELI grade) complying with the KIC specifications (> 46 MPa $\sqrt{m}$ at 20 K) while providing satisfactory ductility (> 6 %);
b) or a level of ductility at 20 K equivalent to the ELI grade with a higher KIC (60 MPa $\sqrt{m}$ than a) while guaranteeing $Re_{0.2}$ and RM properties hogher than to those currently obtained with the ELI grade (VULCAIN impeller);
c) or a highly satisfactory compromise between the KIC ductility/traction and fatigue properties, since the alloy's current properties are enhanced by some 10 %.

These operational sequences are therefore to be implemented on real parts to see if the sequences are in fact well-grounded, and will be validated after dissection of the corresponding standard parts.

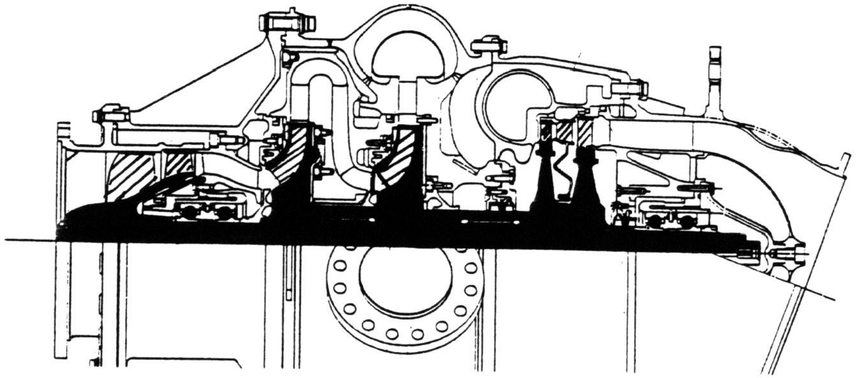
4.2 - Tribological considerations and bearing alloys

Since conventional lubrication is not possible with the liquid propellants H_2 and O_2, all the tribological couplings in these environments have had to be studied specifically.
Boundary friction has to take place under acceptable conditions in terms of the coefficient of friction, wear, overheating, waste production, burn time etc., for these to be compatible with the rated engine operation.

4.2.1 - Case of TA6V PQ (ELI) rotors

As we have seen beforehand, the titanium-based alloy TA6V PQ (ELI) has been chosen on structural criteria and not tribological parameters. The following figure (fig. 5) shows the complete set of tribological couplings between the rotor and stator. No tribological coupling formed with the materials of the rotor (TA6V) and the stator (INCO718) is renowned for the quality of its friction characteristics, however. As a result, the use of certain metal/metal combinations in conjunction with severe operating conditions have inevitably led to problems of seizing and fretting.

FIGURE 4
POSSIBLE ROTOR / STATOR CONTACTS:
CASE OF THE TPLH2



The problem has been solved on the grooves by applying a soft liner by PVD. Specific facilities for fretting tests which can operate at the temperature of liquid nitrogen have been developed at the Higher Institute for Mechanical Construction and Materials (ISMCM), enabling enhanced appraisal of the phenomena and optimization of liner choice.

4.2.2 - Bearings

The requirements for cryogenic bearings in terms of materials are as follows: the greatest hardness possible, combined with correct dimensional stability (minimized residual austenite), fine metallurgical structure (enabling satisfactory fatigue properties on contact) and low corrodibility (stainless alloy).

The basic material currently used for ball bearings and raceways is thus the stainless steel EZ100CD17 (440C), which has a hardness of approximately 58 to 59 HRC. Research has been carried out in conjunction with the steel manufacturers, in order to adapt the steel composition and thermal treatment and optimize its hardness (60 to 61 HRC have been obtained), while maintaining as low a residual austenite rate as possible, since its presence can generate dimensional instability.

Given the severe operating conditions, the research has been oriented towards enhancement, in particular in terms of the development of surface treatment methods for bearing raceways.

All of this research work of course must entail the unavoidable study of the behavioural development and design of the materials for the cryogenic application of similar solutions in LH_2 and LOX environments.

4.3 - Combustion chamber

The choice of alloys for the combustion chamber is essential due to the necessity of evacuating the powerful heat flows output by the throat towards the cooling hydrogen, while controlling the effect of the pressure of the combustion gases in the chamber itself (of the order of 120 b on the VULCAIN engine).
The choice made by DASA therefore opted for copper alloys for their high thermal conductivity. They limit, however, the admissible maximum temperature at the throat to 700 K, which similarly increases the thermal flows since the temperature of the combustion gases is 3,500 K.
In order to evacuate this kind of flow, rapid circulation of cooling hydrogen is organised in the meridian cooling ducts.
For the combustion chamber of the HM7 engine, the choice of OFHC copper was retained on the basis of its high thermal conductivity.
For VULCAIN, the final choice was a copper alloy with higher mechanical characteristics. A long programme of characterization testing in cryogenics was performed at the SEP in order to fully evaluate its properties.
The production program is extremely strict, however, in order to comply with the metallurgical specifications of structure and inclusional cleanliness necessary to guarantee the properties required of the alloy.

Futur developments would enable us to envisage the use of ceramic composite materials operating at a much higher temperature, similar to the HM7 engine nozzle cone manufactured in C.C.M. by the SEP at Bordeaux, which successfully underwent testing on an engine test stand for a cumulated burn time of 1 650 s.

5 - CONCLUSIONS

The developments in the ARIANE programme have enabled the installation of the requisite cryogenic test facilities for material characterization in temperature conditions ranging between 4 K and 300 K at the SOCIETE EUROPEENNE DE PROPULSION (SEP) with regard to the engine.

The test facilities are widely used for current space programmes to qualify the materials and implementation processes.
They will also be used in future programmes in which the requirements will be even harsher.

All the work which has been accomplished so far shows the vital necessity of characterizing materials in order to enable dimensioning of parts while taking into account the extremely importance factor of the conditions in which they are manufactured, i.e metal working, implementation and heat treatment.

The development of new materials, the improvement of inspection methods and enhanced know-how in implementation processes today enable complex parts to be designed at reasonable cost prices with an acceptable level of reliability.

More than ever, advanced engine performance depends on the harmony between the new technologies drafted by design and engineering departments and the new materials and processes chosen, developed and optimized by laboratories and industry. The combined efforts of research centers, manufacturers, processors and users materials will be vital for the basis of future programmes of applied research.

The opening of the frontiers has also enabled to begin very in testing collaboration with the high technological research centers, manufacturers and laboratories for space application in CIS and UKRAINIA. SEP thinks that this cooperation will be a future chalenge to increase the performance for the new space engines development and very useful for the futur programmes

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