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Abstract

The general objectives of WP1 of the HTR-E program are to determine the critical issues, to assess and demonstrate the potential of success for the design of the helium turbine. The aim of this report is to provide some guidelines for an experimental test program required to assess the feasibility of the turbine. In particular, the definition of the mechanical tests necessary to assess the mechanical behaviour of the materials for the blades and the turbine disk is discussed.

Keywords

HTR, turbine disk, blades, experimental tests definition

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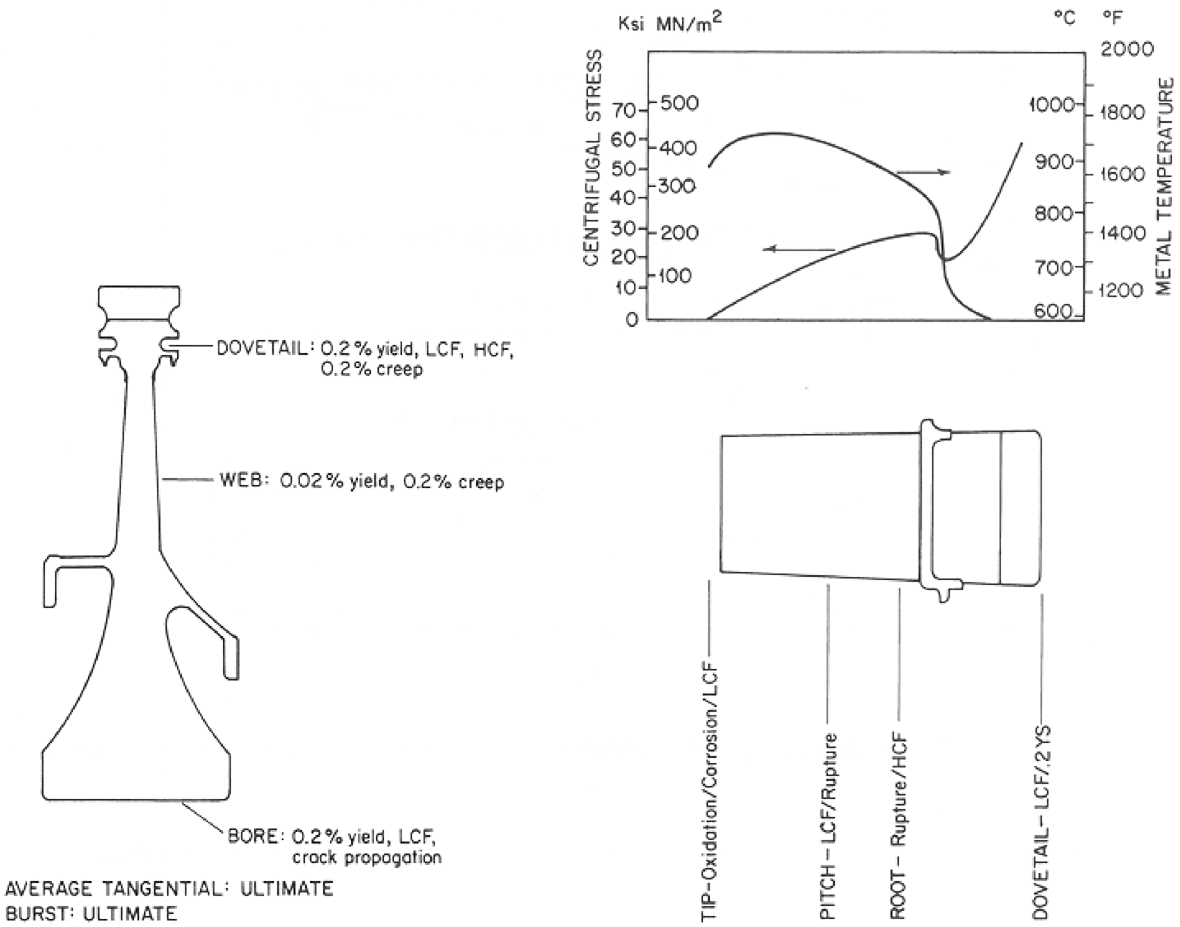
1 Introduction

The general objectives of WP1 of the HTR-E program are to determine the critical issues, to assess and demonstrate the potential of success for the design of the helium turbine. From HTR-M and HTR-E results, the proposed materials to manufacture the blades and the turbine disk have been identified. In this report, the definition of the experimental test program necessary to assess the mechanical behaviour of these materials under the HTR conditions (high temperature and long term) is discussed.

2 Design criteria

It is well known that turbine blades and disks can fail for several reasons. Some of the classical mechanical criteria involved in the design of turbine disks are displayed in Figure 1a while those used for the design of high temperature turbine blades are displayed in Figure 1b. These two components are the most critically stressed and we will first describe the reasons for the use of these criteria.



(a) Design criteria for disks (b) Design criteria for blades

Figure 1 : Design criteria for disks and blades (Anderson 1979) [4]

Ultimate tensile strength

The stresses obtained in the disks or the blades must be very low compared to the ultimate tensile strength. The rupture of a component due to this criterion is likely to occur in case of non controlled over speed. Usually, the overspeed used for this criterion is 25% over design speed. Moreover, this criteria gives the insurance that the disk can undergo at least several start and stop cycles [5]. Thus, this overspeed criteria must be checked at the maximum temperature.

Creep

In the HTR-E turbine, long-duration deformations are likely to occur in the hot part of this component, i.e. in the first stages. Indeed, even with a cooling option, the disk temperature will range between 650°C and 750°C depending of the cooling option, and the foreseen life of these disks should be around 6 years corresponding to the main overhaul. Under these conditions viscoplastic strains are likely to occur far below the classical yield point. The design criteria is usually based on a limiting creep strain over the foreseen life time : typically 0.2% (Figure 1). In the GT-MHR project, the high temperatures, stresses and time duration on the first stages discs of the turbine make this criterion very important.

Low cycle fatigue

Low cycle fatigue (LCF) damage is likely to occur in parts of the structure loaded cyclically in the plastic range close to the yield point. With this level of stress, rupture will occur for a relatively small numbers of cycles, typically below 10^5. This type of damage may be due to the starts and stops operations that will occur during the life of the turbomachinery. However, although plasticity is likely to occur at the rim and the hub after the first start, no further plastic strain is expected during the subsequent starts and stops due to strain hardening. Moreover, large fluctuations of thermal stresses can also occur upon load changes. This effect is enhanced with high-temperature materials that tend to have lower thermal conductivities and higher thermal expansion coefficients than metals used at lower temperatures (below 500°C) [4].
As described by McCloskey [7] for land based gas turbines, most failures in turbine blading of fossil units occur in low pressure blades particularly concentrated in the L-0 and L-1 stages. Each turbine blade row of a particular turbine design tends to have distinctive problems. For example, the operating life of L-0 rows is generally controlled by Low Cycle Fatigue caused by start-stop cycling, although in extreme off-design conditions stall flutter may also cause fatigue damage by high cycle damage mechanism.

High cycle fatigue

Following the remarks of McCloskey [7], the L-2 and L-3 rows of fossil units are generally controlled by high cycle fatigue typically as a result of resonance with particular blade-disc modes with per-rev harmonics of rotational speed. Thus, fatigue modes leading to stresses greater than the fatigue limit must be avoided.

Fatigue crack growth

This type of criterion recognizes that it is not possible to avoid the initiation of a crack due to the combination of cyclic thermomechanical cycles and creep. Since the used materials should not be too notched sensitive, the crack will grow slowly until a limiting size. Thus to use this criterion, it is necessary to know first a limiting size and second a crack propagation law. The main idea behind such a criteria is that it should ensure that a defect of the size corresponding to the limit of the non destructive method applied on the component, will not lead to rupture before the next overhaul.

Oxidation-corrosion

In the HTRE turbomachinery, the environment may be carburizing, decarburizing or oxidizing. In fact, the real conditions are not yet well known and depend strongly on the oxygen partial pressure. Moreover, depending on the location in the loop, and depending on the loading (start, stop, nominal conditions), the environment is likely to change. Thus, it is important to check the influence of these different conditions on the mechanical properties.

3 Mechanical tests for disk materials

In this chapter, we will present the proposed mechanical tests for U720 Coarse Grain material foreseen to be used for the turbine disk. The envelop in service conditions have been clarified by Framatome ANP [2]. Within HTR-M and HTR-E programs it has been shown that even using this superalloy, the foreseen conditions for the turbine disk of the first stage in terms of temperature, stresses and time cannot be withstood at 850°C with a non cooled option. The temperatures and stresses are evaluated by numerical simulations in [3], [6] and [8].

The geometry of the disk has been provided by OKBM in [3] since no turbine manufacturer are in this work package. Aubert&Duval has shown in [1] that it seems possible to manufacture such a large disk in U720CG. However, due to the size of the disk, microstructural heterogeneities due to the different cooling rates between the material close to the surface and the bulk, and chemical segregations will be present. It will be thus necessary to machine all the mechanical samples in an ingot with a size close to that necessary for the full size component, in order to estimate a relevant scattering effect.

The four type of experimental tests are proposed below for the turbine disk :

- Tensile tests
- Creep tests : determination of stress to reach 0.2%, 1%, after 60000h
- Low cycle fatigue under imposed stress
- Creep-fatigue tests
- Fatigue crack growth

The temperature should range from room temperature to 850°C. And the longest foreseen durations for the creep tests should approach 60000h (at least 20000h) to take into account the microstructure evolution that will occur at high temperatures. Moreover, the effect of ageing temperature on the tensile and LCF properties should be addressed. Finally, the possible effect of helium impurities will not be considered for the disk. In the HTR-M project, it has been assessed that the disk should not be subjected to corrosion effects due to its lower temperature than the blades. If necessary, a coating could be performed on the disk.

A preliminary estimation of the number of specimens is displayed in table 1.

Type of test	T(°C)	Condition	Nb / condition	Blank size	Nb of specimens	Effect of ageing T
Tensile	20 100 to 500 each 100 550 to 900 Each 50	5 10^{-4} s^{-1}	3	ϕ12h100	14 x 3 = 42	14 x 2 = 28
Creep	650 to 850 each 50	3 stresses (lower stress to approach 60000h)	3	ϕ12h100	5x3x3 – 6 = 39	-
LCF	20, 300, 400, 500, 600, 700, 750	3 $\Delta\sigma$ R = 0.01 1 load rate	3	ϕ20h100	7x3x3x1=63	~30
Creep/fatigue	700, 750			ϕ20h100	~30	-
FCG	650 to 850 each 100	3 ΔK max 2 R 1 f	3	CT20 (20x50x50)	3x6x3=54	~30

table 1 : Experimental test matrix for the turbine disk material

Several comments are necessary to help the understanding of this proposed test matrix.

- To have reliable results and an idea of the scattering of the properties, all the tests should be performed 3 times.
- Although the temperature of the disk should not go higher than 750°C, it seems important to know the behaviour of the material above this limit. However, at 800°C and 850°C, the long time duration tests are not justified since it is already known that the change of microstructure will lead to a softening of the material well before 60000 hr. This explain the "- 6" in the column corresponding to the number of creep specimen.
- The approximate size of the blank to machine the specimens is displayed. This can help to evaluate the amount of material necessary.
- The classical LCF tests are usually performed at imposed $\Delta\varepsilon$. However, in a rotating disk the loading is due to centrifugal forces, thus it is proposed to impose $\Delta\sigma$.

- Creep/fatigue tests (dwell at the maximum stress) should be performed to analyse the cumulated damage from these two types of interactions likely to occur near the stress concentration area in the disk.

- Since corrosion is not likely to occur on the disk material, the tests should be performed under inert gas or vacuum.

- To analyse the effect of the ageing temperature and time, less tests are proposed. The conditions will be defined, once the reference state will be analysed, to quantify the decrease of mechanical properties.

The above proposed test matrix leads to :

- 70 tensile tests
- 39 creep tests
- 93 LCF tests
- 30 creep/fatigue tests
- 84 FCG tests

Although the number of tests looks high, these tests appear necessary due to the criticity of such a component in a direct cycle.

Moreover, the microstructural heterogeneities within the different locations in the disk in radius or in depth (different cooling rates) should be addressed. The conditions of the additional tests should be carefully decided to be able to evaluate the change of properties associated to these heterogeneities.

Finally, additional tests should be performed to check the anisotropy of mechanical properties within the disk. The ductility and the crack rate during FCG tests are likely to be strongly influenced.

4 Mechanical tests for blade materials

The mechanical properties proposed to be addresses for the turbine blades materials are the following ones :

- Tensile properties : YS, UTS
- Creep tests : stress to reach a deformation of 0.2%, 1%, after 60000h
- Low cycle fatigue life time
- **High Cycle Fatigue** up to 10^7 cycles
- Fatigue crack growth
- Creep/fatigue life time

Within the HTR-M and HTR-M1 project [9], two grades of Directionally Solidified Ni-based superalloys have been evaluated for the blades : IN792DS and CM247LCDS. It has been shown that the CM247 material showed better properties at high temperatures under tensile and creep loadings. Moreover, this material should fulfil the ISTC design criteria [3].

The difference with the disk material is that we add high cycle fatigue and higher temperatures since the blades are in direct contact with the hot helium and should not be cooled as proposed in the HTR-M program. Moreover, corrosion aspects will have to be considered as explained further.

Type of test	T(°C)	Condition	Nb / condition	Blank size	Nb of specimens	Effect of ageing T	Effect O_2, C
Tensile	20 100 to 500 each 100 550 to 900 Each 50	$5\ 10^{-4}$ s	3	ϕ12h100	14 x 3 = 42	14 x 2 = 28	10 x2 x 2 = 40
Creep	700 to 900 each 50	3 stresses (lower stress to approach 60000h)	3	ϕ12h100	5x3x3 = 45	-	20 X 2 = 40
LCF	20, 300, 500, 650, 750, 800, 850, 900	3 $\Delta\sigma$ R = 0.01 1 load rate	3	ϕ20h100	8x3x3x1=72	~30	30 x 2 = 60
Creep/ Fatigue	750, 800			ϕ20h100	~20	-	~20
HCF	750, 800, 850	50 Hz, 1 R_σ, 7 $\Delta\sigma$	5	Depending on the type of test	7x5x3=105	7x5x2= 70	7x5x2 =70
FCG	700, 800, 850, 900	3 ΔK max 2 R 1 f	3	CT20 (20x50x50)	4x6x3=72	~30	30 x 2 = 60

table 2 : Experimental test matrix for the turbine blade material

A description of the proposed tests is displayed in table 2. The following comments complete this table :

- In order to analyse the effect of impurities on the mechanical properties, the reference tests should be performed in an inert atmosphere or under vacuum.

- In parallel to the tests under impure environment, corrosion tests will be performed to address the corrosion rate.

- Concerning the Fatigue Crack Growth tests, the properties are very sensitive to the environment. Indeed, interactions between the environment and the crack tip may enhance the crack rate.

- The effects of the ageing temperature and environment should have a great influence on the tensile and HCF properties. 2 temperatures should be analysed to evaluate this effect.

- It is proposed as in [3], to perform the HCF tests using bending tests under rotation speed of 50 Hz. These kinds of experiments are less expensive than the classical tests with uniaxial fatigue machine and the specimen are smaller.

- Creep/fatigue damage may occur in the blade foot where the temperature of the blades is however lower. It is proposed to check this type of damage at 750°C and 800°C.

- Although the blades will be coated, corrosion must be addressed for the following reasons. The clearance between the tip of the blade and casing is set at the lower possible value to minimize the aerodynamic losses. In some special cases of loading, a tip rub may occur and the protective coating will be removed. Erosion due to dust particles in the helium flow may also damage the coating. Moreover, the coating may also be removed through low-cycle fatigue acting on the blade tip [4].

The number of proposed tests for the blades is :

- 110 Tensile tests
- 85 Creep tests
- 162 LCF tests
- 245 HCF tests
- 162 FCG tests
- 40 Creep/Fatigue tests

5 Conclusions

The aim of this report is to propose the minimum required experimental tests program to be able to calculate the stresses in the hot parts of the turbine of a High Temperature reactor (discs and blades of the first stages) as well as to provide mechanical criteria to assess the life of these components. It has been shown in [8] that concerning the material foreseen for the disk (U720 Coarse Grain) the experimental data base is not sufficient, in particular concerning fatigue and long durations creep tests. Although the number of tests defined in this report seems high, it looks justified by the safety issues linked to the rupture of the turbine within a direct HTR cycle.

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