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Feasibility study of large turbine disks production for HTRs

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FEASIBILITY STUDY OF LARGE SIZE TURBINE DISKS PRODUCTION

FOR HIGH TEMPERATURE REACTORS

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INTRODUCTION

High Temperature Reactors are a promising technology in order to build self safe and high efficiency next generation nuclear reactors for electricity and direct hydrogen production. For the electricity generation a direct helium cycle is foreseen.

Even if a detailed design of turbine is not available, it appears that turbine disks are a critical part in term of material definition and production route. The challenge for such a part is the compromise between the material itself and, particularly, its creep resistance and the process to manufacture big size part.

The first part of this report, will present the state of the art for the production of hot rotating disks for Land Base Turbine and Aero engine.

In the second part, an analysis of the production routes of U 720 Coarse Grain of 1,5 m diameter disk will be done in order to determine critical steps and the way to control these critical steps.

1. PRESENTATION OF THE STUDY

In the frame of FP5, a lot of studies have been launched in order to analyze and to give information required for the design of High Temperature Reactors (HTR). These nuclear plants are gas (Helium) cooled and can product high temperature heat for hydrogen production (between 850 and 1100° C), and electricity through a direct cycle on a specially designed turbine.

HTR E and M Working Group try to previse :

- Principles of design of turbines
- Characteristics of material likely to be of interest to these designs.

The turbine for a direct helium cycle would have following characteristics :

- A gas temperature around 850° C. Cooling of disk is possible but very costly as far as efficiency is concerned.
- A large size between 1,3 and 1,5 m diameter
- A service stress around 200 MPa
- A time between maintenance operation more than 70000 h

The combination of stress and temperature means very high creep elongation resistance requirements.

The large size of the parts brings manufacturing difficulties, because the highest performance material are nickel base super-refractory alloys.

For this kind of alloys, the highest performance they have, the most difficult the thermo mechanical processing is.

2. STATE OF THE ART

In this chapter, it is presented a review of alloys and production routes for hot rotating parts in Land Based Turbine (LBT) and Aero engine. For LBT only turbine disks are concerned, for Aero engine high pressure compressor disks and turbine disks are concerned.

2.1. - Services solicitations

In table 1, are summarized main thermal and mechanical solicitations for land base turbine and Aero engine hot disks.

The main differences between LBT and Aero engines are :

- The size (from 1 to 2) and consequently the mass (from 1 to 8)
- The stress level (higher than yield stress for Aero engine)
- The temperature level
- The life time (ten times longer for LBT than Aero engine one)

Due to high service temperature, Aero engine disks can meet metallurgical evolution (coarsening of hardening precipitates, brittleing phases).

2.2. - Grades

To meet the mechanical and temperature resistance requirements highly alloyed grades (iron or nickel based) with phase hardening and used.

In table 2 are given chemical analysis of main grades used for hot disks.

In tables 3 and 4 are given the grades uses in LBT (table 3) and Aero engine (table 4)

Grades 706 and 901 are specific of LBT. They were developed for this application in order to manufacture large size disks.

Grades A 286, 718 and Waspaloy are used for both applications. In case of 718, processing and chemical analysis (for C and Nb mainly) have been adapted for LBT large size parts .particularly to solve solidification problem of required large section ingots

Other grades are used only for Aero engine.

2.3. - Thermo mechanical processing :

Two production (cast and wrought and powder metallurgy) routes are used :

2.3.1. - Cast and wrought route (C/W) for LBT and Aero engine parts (table 5)

This “conventional” route includes seven steps. It is important to understand that the final microstructure (and consequently mechanical properties) checked at the last final inspection step is given by the combination of the six previous steps. A global mastering of the whole route is the only way to guaranty the final result.

Step 1 : Vacuum Induction Melting (VIM)

The role of VIM is to give chemical analysis of the melt.

Step 2 : Remelting (ESR and/or VAR)

The role of remelting is to get on ingot :

- Cleanliness
- Degassing
- Homogeneity (at a micro, meso and macro level). To get a satisfactory level, a double remelting can be necessary for large size ingot and highly alloyed grades.

Step 3 : Billetizing

Billetizing includes several sequences of annealing and hot forging on hydraulic press. The role of this step is to get a metal with a fine grain micro structure convenient for ultrasonic inspection and for further steps.

Step 4 : Semi Product inspection

Minimum : chemical analysis, macro and microstructure and ultrasonic inspection.

Step 5 : Close die forging

The first aim of close die forging is shaping of the disk with a good control of micro structural change.

Step 6 : Heat treatment

Heat treatment (solutioning + Quench + agings) gives the final microstructure with related mechanical properties.

Step 7 : Inspection

This step includes :

- Non destructive testing after an ultrasonic shape machining with macro etching, liquid penetrant inspection and ultrasonic inspection.

- Cut off of an integral ring for mechanical testing and microstructure inspection.

Step 8 : Delivery

2.3.2. - Powder Metallurgy Route (PM) only for Aero engine parts

The aim of Powder Metallurgy is to overcome ingot solidification heredity on final microstructure for highly alloyed grades. As for cast and wrought route the final properties of the part are generated by the combination of all the process steps.

Step 1 : Vacuum Induction Melting

The role of VIM is to give chemical analysis of the melt.

Step 2 : Powder production

Three processes are used today at industrial scale :

- Rotating electrode pulverization by a plasma torch (used in Russia).
- Explosive out gazing of liquid melt hydrogen saturated. This process is used by Homogeneous Metals, a subsidiary of PRATT & WHITNEY,

- Argon atomization of liquid metal. This process is the most widely used for super alloy powder production

Step 3 : Powder Sieving

The aim of sieving is to reduce the maximum size of contaminant and more precisely ceramic particles. The size of the mesh is between 45 and 150 µm according to the application.

Step 4 : Powder densification and shaping

Two main routes are industrially used :

Step 4.1 : HIP densification in a shaped capsule (Russia and a few parts in U.S.A.)

Step 4.2 : Extrusion + super-plastic isothermal forging (western countries).

Extrusion has several purposes :

- Full densification of powder
- Generation of a very fine (G ASTM : 12-13) homogeneous microstructure proper for a very accurate ultrasonic inspection and further super-plastic forming
- Healing of possible large size organic contaminations which are not seen by NDT (ref.1).

Super plastic isothermal forging allows to save expensive material very costly to be machined.

Step 5 : Pre-machining

Step 6 : Heat treatment (solutioning + quenching + aging).

Step 7 : Final inspection

Non destructive testing : liquid penetrant and ultrasonic inspection
Cut-of of an integral ring for mechanical testing and microstructure inspection

Step 8 : Delivery

3. PRODUCTION OF LARGE SIZE TURBINE DISKS FOR H.T.R.

Geometrical and dimensional requirements for HTR turbine disks are note definitive today. However, starting from studies performed by VON KARMAN INSTITUTE following hypotheses have been used :

- Diameter : 1450 mm
- Thickness : 230mm

None of existing disks meet together size and creep resistance requirements for HTR disks.

C.E.A. (ref.2) has done a study on the material which could be used for H.T.R. Turbine disks. The development of a new alloy specially designed for the application would be a long term program and the guarantee to be successful is uncertain. The best existing grade would be U 720 in the coarse grain version.

In this chapter, will be examined the main foreseeable difficulties and the way and associated studies proper to overcome these difficulties.

3.1. - Presentation of U 720

U 720 was developed by Special Metals in the beginning of the seventies for blading applications. The processing includes in the final heat treatment a super solvus annealing to get a coarse grain (typically GASTM 2-4).

More recently (ref.3) a U720LI has been developed for turbine disk application. Chemical analysis has been adapted in order to reduce segregation level in ingots and to increase metallurgical stability. The chemical changes are a lowering of carbon, chromium and boron contents (see table 2).

Two versions have been developed:

- For turbine disks, where a high yield strength is required, a fine grain (typically GASTM < 8) microstructure is produced by a sub-solvus hot working and a heat treatment with also a sub-solvus solutionning before quench and 2 steps aging.
- For turbine disks (particularly helicopter turbine disk for which cooling in service is not possible), where a high creep resistance is required , adaptation of hot working and final heat treatment allows to get a coarse grain microstructure.

The compromise of mechanical properties for the coarse grains version seems promising for H.T.R. turbine disks application and justifies the interest of this alloy.

3.2. - Description of considered production routes :

The final size of the pre-mechanical disks is 1400 mm diameter and 230 mm thickness (mass 2,9 t). It corresponds to a forged blank maximum diameter 1600 mm, thickness 250 mm (mass 4 t).

Two production routes have been studied :

- Conventional cast and wrought route
- Pre-alloyed powder metallurgy route

3.2.1. - Cast and Wrought (C/W Route)

3.2.1.1 - Melting

The item of this step is the production of an ingot with the following requirements :

- Weight : 6 - 7 t minimum
- Diameter compatible with the forging ratio in billetizing
- Chemical analysis
- Homogeneity

The main concern is the solidification defects like freckles, or a too high level of segregation impossible to be reduced during thermo-mechanical processing. Segregations produce gamma prime precipitates barriers leading to final grain size heterogeneity.

Tendency to solidification defects and high level of segregation increases quickly with ingot diameter. To reduce this tendency, triple melt procedure is used with a double remelting :

- ESR (Electro Slag Remelting) for refining and to get compact electrodes.
- VAR (Vacuum Arc Remelting) to control solidification.

Modeling allows to optimize remelting parameters as far as tendency to generate macro and meso solidification defects is concerned. Figure 1 gives the results of modeling with the programme SOLAR of VAR nickel base superalloys remelting and all the informations which can be obtained.

The process is industrial for ∅ 500 (weight 2,2 t ingot) and trials are running to develop ∅ 650 (5 - 7 t ingot).

3.2.1.2.- Billetizing and blank production (including ultrasonic inspection)

The purpose of this step is to get a blank ready for the final upsetting operation. The two main requirements are :

- A fine and homogeneous microstructure allowing a high definition ultrasonic inspection.

- A maximum height/diameter ratios of 2,25 in order do avoid buckling risk during final forging. For the considered disk, it means ∅ 650 - h = 1450 blank.

The thermomechanical processing giving the suitable microstructure and blank geometry includes annealing and hydraulic press combination of cogging and upsetting operations with a minimum forging ratios to be respected. Modeling allows to foresee local thermo-mechanical conditions and resulting microstructure.

The operation is classical and industrially well mastered.

3.2.1.3.- Last forging

Last forging could be a simple upsetting with flat tooling or a closed die forging with shaped tooling. Upsetting has been modelised with Forge 2 computer code in order to get temperature map, press force required for forging and local microstructure in the whole part. It would be a two steps upsetting.

Table 6 summarizes the step and the weight of items

Figures 2 and 3 give temperature distribution at the end of first and final step.

Figure 4 gives a forecast of press strength during the final step. Maximum force is a little bit higher than 40 000 t.

A 65 000 t hydraulic press (INTERFORGE - ISSOIRE) is necessary and convenient for the final shaping of the disk (***Figure 5)***

Close die forging of large size disks up to 2.4 m diameter is industrially performed on INTERFORGE - ISSOIRE hydraulic press ***Figure 6 and 7*** give view of forgings at two steps and the final pre-machined part of a 2,4 m diameter and 12T weight disk in 718 (ref.4).No specific problem is expected at this step.

After forging a new ultrasonic inspection is foreseen after pre-machining in order to eliminate cortical zone.

3.2.1.4 - Final heat treatment

Final heat treatment gives the microstructure suitable for mechanical properties. The purpose is:

- A homogeneous coarse grain size (typically GASTM : 2-4)
- A controlled fine γ' precipitates distribution.

Homogeneous controlled coarse grain size is linked with a very precise super solvus γ' annealing. To get the wished grain size and to avoid too large grain size a temperature window of 1° C order of magnitude is available.

The main concern is the solutionning furnace due to the high precision temperature requirement. A dedicated furnace is necessary, the existing facility in AUBERT & DUVAL is able to treat parts till 1 m diameter. For a 1,4 m diameter part an investment is necessary knowing that the technology is available.

Fine γ' precipitates distribution is given by quenching rate after solutionning annealing and by aging treatments. Yield strength and intermediate temperature creep resistance are increased with quenching rate. The limitation in quenching rate comes from quench cracks risks. Water quench is not possible, oil quench could be not possible.

To fix the quench conditions and the related mechanical properties, a specific study is necessary including :

- Modeling of stresses and strain during quenching
- Determination of crack occurrence risk - criteria
- Effect of quenching rate and agings on mechanical properties

Concerning agings, it is likely that they have to be adapted to high temperature long term creep resistance

3.2.1.5. Final inspection

After a new machining to eliminate cortical zone final inspection is carried out :

- Liquid penetrant inspection (to detect cracks)
- Macro-etching (homogeneity of structure)
- Integral ring cut-off (microstructure and mechanical trials)

At this step, it is no more possible to carry out a valuable ultrasonic inspection, because of coarse grain microstructure.

3.2.2. - Powder Metallurgy (PM Route)

In parallel of C/W route, a pre-alloyed powder metallurgy route has been considered. The main concern for the C/W route is the possibility to produce large size (5 to 7 t) ingot with an acceptable level of homogeneity (see 3.2.1.1.).

PM route overcomes totally this difficulty because each particle is a micro-ingot with micrometric solidification structure. This starting material allows to produce parts with remarkable homogeneous microstructure without scale effect.

Powder Metallurgy is used today for aero-engines disks with a 700° C maximum service temperature. The microstructure is adapted to this temperature with a fine grain size between G ASTM 6 and 10.

For the H.T.R. application, the optimum grain size is around GASTM 4 in order to increase creep resistance.

With a special HIP cycle (ref.5), it is possible to let grow the final grain size with a good control of it.

C.E.A.(ref.6) has shown that in as HIP conditions, mechanical properties are similar whatever the production route, as far as the grain size is similar.

3.2.2.1. - Powder batch constitution

Material to be atomized is produced in a classical VIM. Argon atomization is carried out on an atomization facility with a 300 -600 kg VIM furnace for remelting. Cleanliness of powder (gas and ceramics contamination) is controlled through a dedicated facility and a quality insurance program (ref.7).

Thousands tons of nickel base super alloy powder have been produced for military and civil aero-engine rotating critical parts.

Before use, powder is sieved to limit the maximum size of contaminant. The size of the mesh depends of the maximum acceptable size of inclusions. For H.T.R., 100-125 ρm could be the order of magnitude.

To constitute large size batch, several atomization batches are mixed together. For aero-engine disks production, size of industrial batch is typically 2 to 5 t.

3.2.2.2. - Powder densification (HIP)

Due to the large size of final parts, only HIP is envisaged for densification of powder. The maximum size of HIP vessel is 1,2 - 1,6 m diameter and 2,5 - 3 m high.

It could be possible to produce HIPed blocks 1,05 - 1,35 m diameter and 2,1 - 2,5 m high for a weight 15 t maximum.

Before HIPing, powder is placed and degassed in a container sealed after filling.

Two to three tons super alloy blocks have been industrially produced and there is no foreseenable limit to reach the limit of HIP vessel size.

3.2.2.3.- Die forging

Forging is mandatory to get the final diameter and to guaranty the quality of material (see 2.3.2.). The minimum forging ratio is 3.

Forging parameters (temperature, strain rate, number of heats) have to be adapted to powder metallurgy materials and to the final microstructure control. However, the risk to fail at forging stage is small.

The rheology of PM material is very close of C/W material and the required hydraulic press strength is the same (see 3.2.1.3.).

3.2.2.4. - Ultrasonic inspection

As for C/W route, ultrasonic inspection is carried out at this step before grain coarsening during the final heat treatment.

Homogeneity on microstructure reduces grass level.

3.2.2.5. - Heat treatment

As for C/W route, final heat treatment includes :

- Super solvus solutionning + quenching
- One or two steps aging

Grain coarsening is a lot slowlier than for C/W material. The risk of grain explosion is very weak and it is possible to have a precise control of the grain size. However, the exact solutionning parameters (temperature and dwell time) have to be fixed.

There is a concern for the sensitivity of grain coarsening in function of local thermo-mechanical processing. Specific studies are required.

As for C/W material, quenching conditions after solutionning are a critical parameter, and specific studies are required (see 3.2.1.4.) and aging has to be optimized for long term creep resistance.

3.2.2.6. - Final inspection

Final inspection is similar to C/W material one. It includes :

- Pre-machining
- Liquid penetrant inspection
- Macro-etching
- Integral ring cut-off for micro structural inspection and mechanical testing.

CONCLUSION

Production on an industrial scale of large size turbine disks in U720 can be reasonably claimed as possible.

In this report, starting from industrial experience on superalloys disks production for Aero-engine and Land Base Turbine, two routes have been defined for the production of U720 1,5m diameter disks. The first one is a conventional cast and wrought route and the second one a prealloyed powder metallurgy route.

The principles of these two routes, which have to be considered as a whole, are defined. The way to fix processing parameters requires a methodology experienced and validated on existing products. This methodology involves widely modeling of the different steps of the process.

Industrial facilities required for the production of HTR turbine disks are already available inside A&D plants except for a large size high precision heat-treatment furnace, the technology of which is nevertheless existing.

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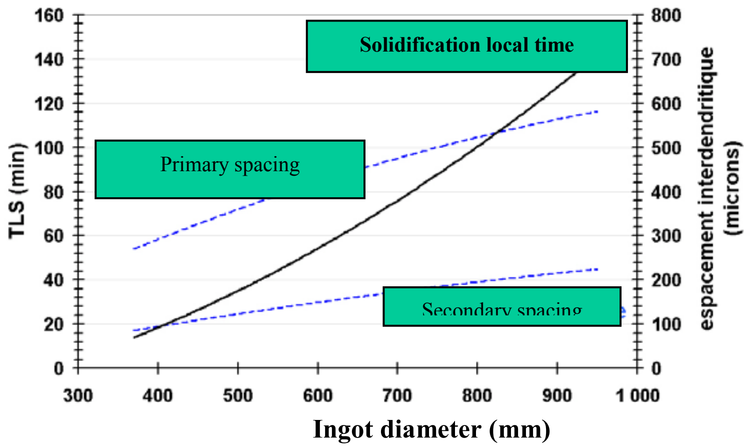
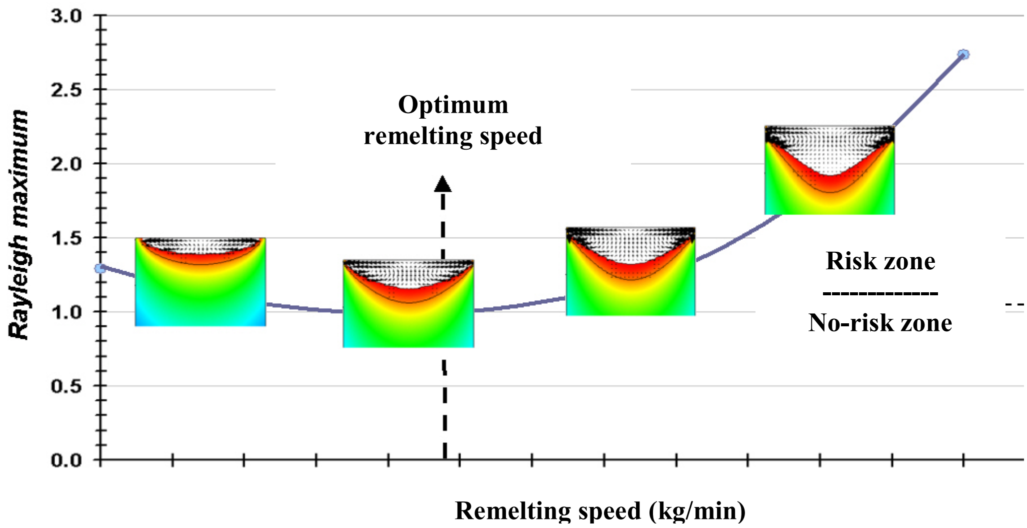
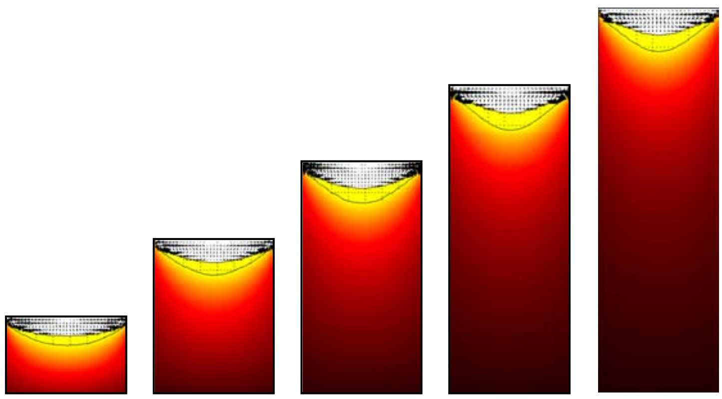
Figure 1 VAR Modeling
(SOLAR programme)



RAYLEIGHT CRITERIA
(freckles occurrence)



Temperature map



VAR Modeling effect of thermic and convection

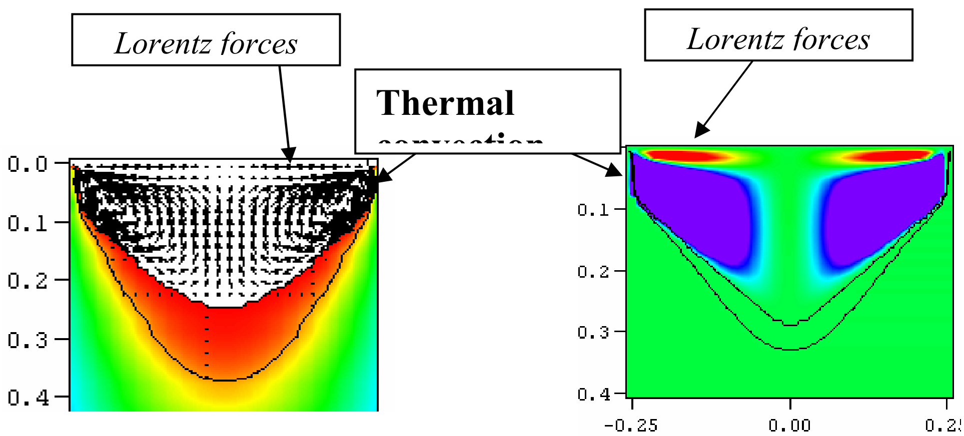


Table 1-Comparaison of service conditions

	Land Base Turbine	Aeroengine
Temperature (°C) nominal maximum	540 600	600-700 750
Stress level	intermediate	high
Life time	x 100000h	x 10000h
Cycles number	5000-15000	5000-50000
Size (diameter)	till 2000mm	till 1000mm
Ranking of specifications	1/ Low Cycle Fatigue Resistance 2/ Yield Strength 3/ Damage Tolerance Resistance 4/ Toughness 5/ Elongation Creep resistance	1/ Low Cycle Fatigue Resistance 2/ Yield Strength 3/ Elongation Creep resistance 4/ Damage Tolerance Resistance 5/ Toughness

Table 2-Chemical analysis of grades used for hot rotating parts in LBT and Aeroengines

Grade	C	Cr	Co	Ti	Al	Ni	Fe	Mo	W	Nb	Other
901	0,03	13,25		2,85	0,25	41,75	remainder	5,7			
706	0,01	16		1,8	0,2	remainder	38			2,9	
718 LBT	0,01	19		1	0,5	54	remainder	3,1		5	
718 Aeroengine	0,04	19		1	0,5	54	remainder	3,1		5,4	
720	0,04	18	14,6	5	2,5	remainder		3	1,25		
720LI	0,015	16,2	14,6	5	2,5	remainder		3	1,25		
A286	0,05	15		2	2,6	remainder	1,25				V 0,25
U500	0,08	18	18,5	3	3	remainder		4			
Waspaloy	0,03	19	13,5	3,1	1,3	remainder		4,1			
N18	0,015	11,5	15,5	4,35	4,35	remainder		6,5			Hf 0,5
MERL 76	0,025	12,4	18,5	4,3	5	remainder		3,2			V 0,75
EP741	0,05	8,7	15,6	1,85	4,9	remainder		4	5,8	2,4	Hf 0,25
Rene 88	0,04	16	13	3,7	2,1	remainder		4	4	0,7	

Table 3 - Industrial Land Base Turbines Disks

Grade	Industrial part size (diameter in mm)
901	1200
706	>2000
718	2200
Waspaloy	1200-1400
A286	1800

Table 4- Industrial Aero-engines hot rotating disks

Grade	Process	Industrial parts size (diameter in mm)
718	C/W	1000
Waspaloy	C/W	850
U500	C/W	small disks
U720FG	C/W	850
U720CG	C/W	400
Rene 95	PM as HIP and extruded+isothermally forged	400-650
EP 741	PM as HIP	650
MERL 76	Extruded+isothermally forged	1000
Rene 88	Extruded+isothermally forged	1000
N18	Extruded+isothermally forged	600
Astroloy	PM as HIP and HIP+forged	800

Table 5- Summary of C/W Route		
Step	**Requirements**	**Critical Parameters**
Ingot	chemical analysis homogeneity	remelting parameters
Blank	grain size homogeneity h/D ratio	forging ratio
Ultra sonic inspection	grain size	
Final forging	geometry	forging strength subsolvus forging
Ultra sonic inspection	grain size	subsolvus forging
Heat treatment	controlled grain coarsening integrity	solutioning temperature and dwell quench rate
Final inspection		

Table 6- Items produced along Cast and Wrought Route

Step	Item	Dimensions (mm)		weight
		Diameter	Height	
Melting	Ingot	650	2000-2600	5-7t
Billetizing	Blank	650	1450	4t
Final Forging	Pre-form	1600	250	4t
Pre-machining Heat treatment	Pre-machined part	1450	230	3t

Figure 1-Temperature map at the end of first forging step

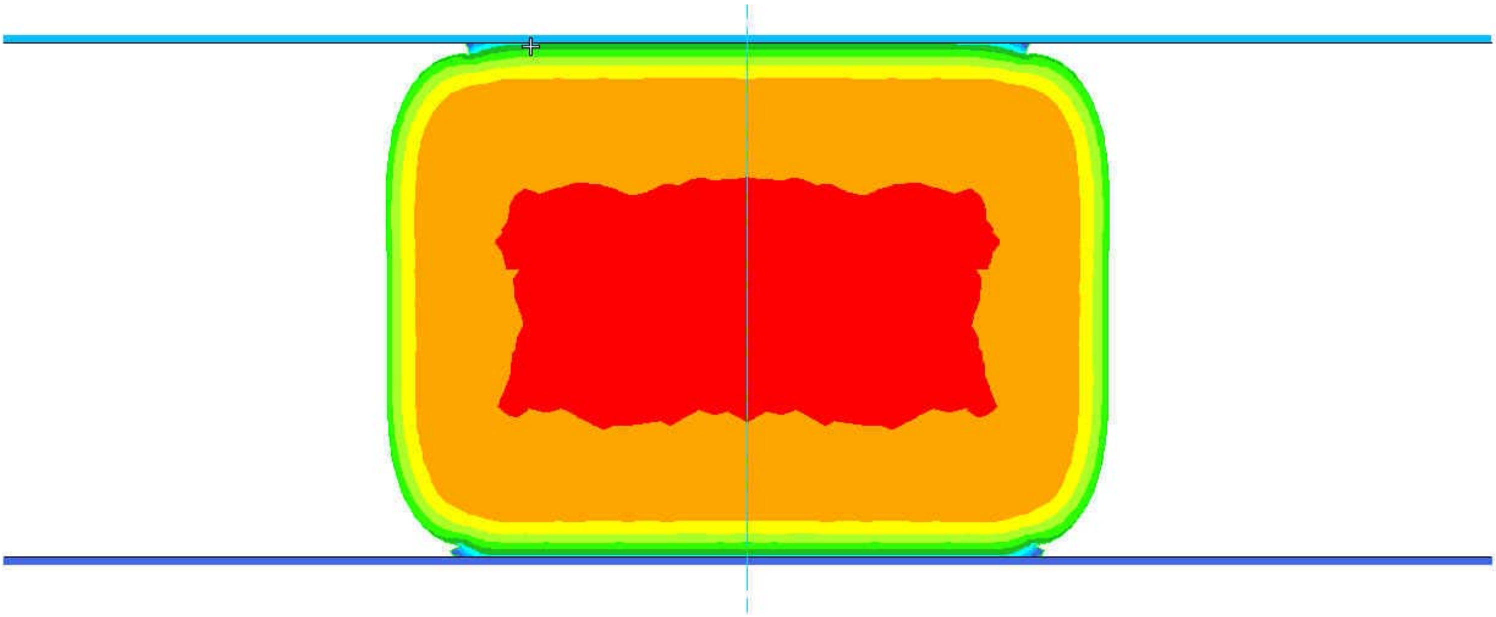


Figure 2-Temperature map at the end of second forging step

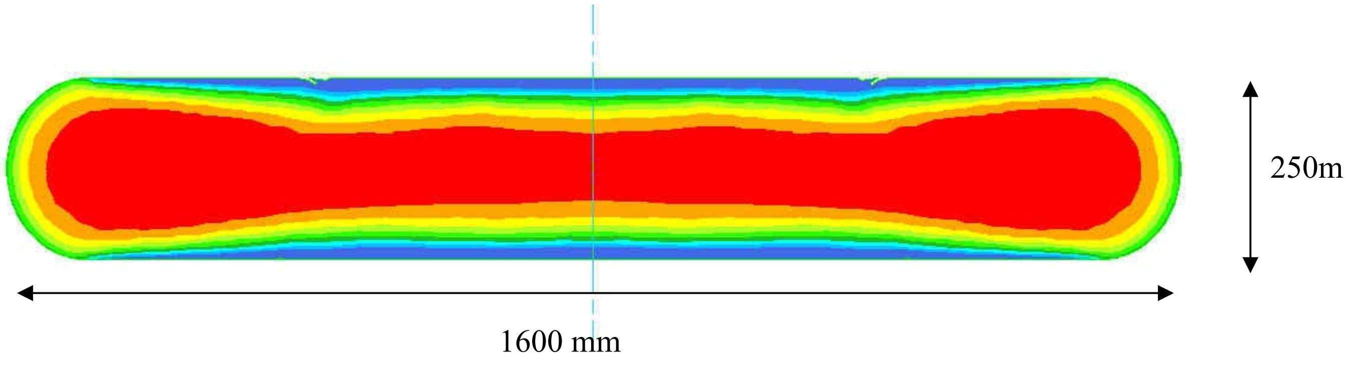


Figure 3- Prediction of effort during second step final forging

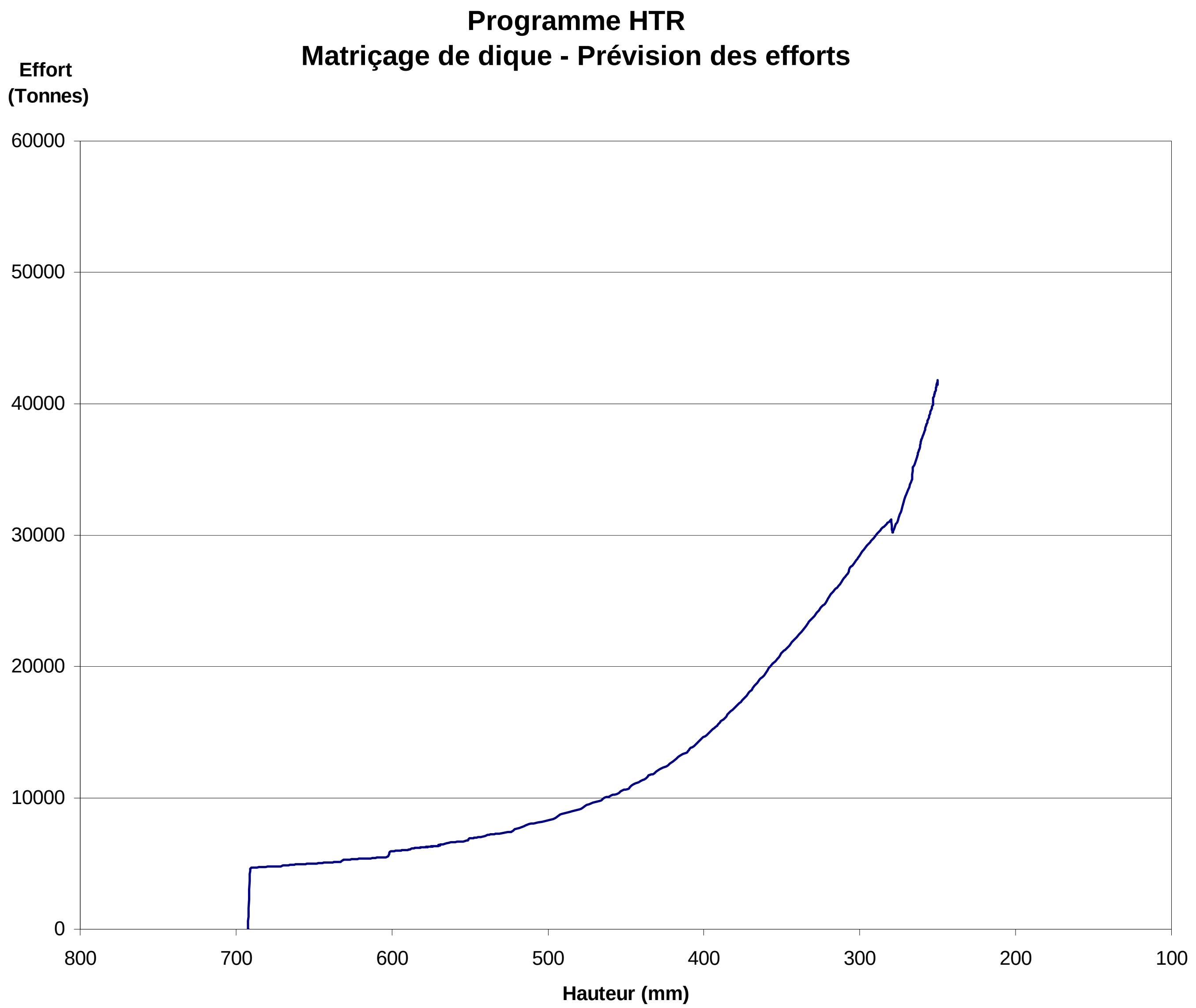


Figure 4 View of the Interforge 65000t Hydraulic press

Figure 5 Upsetting of a 2,4 718 LBT Disk (first and second heat)

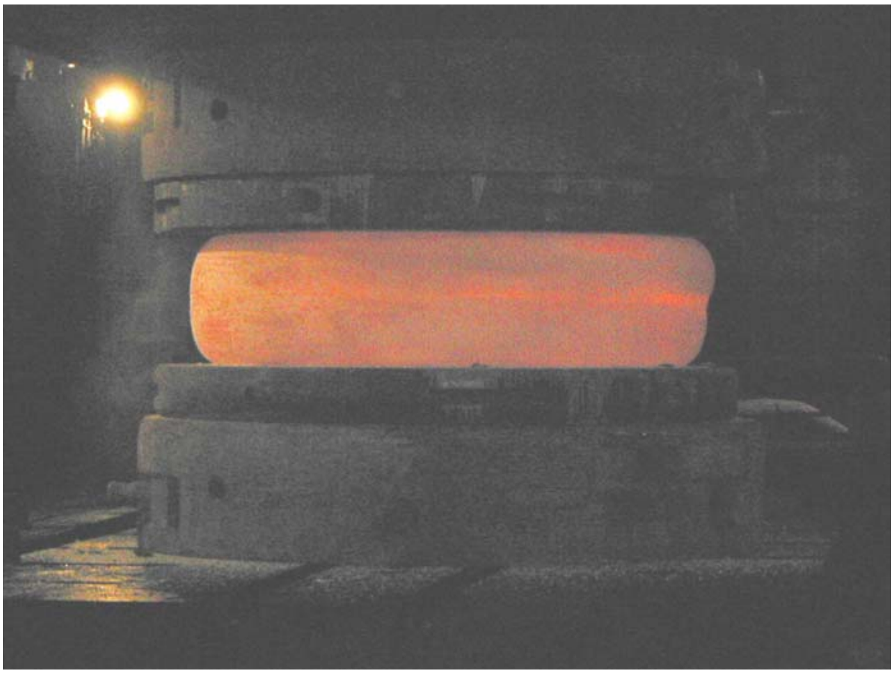


Figure 6 : Premachined 2,4 m diameter 718 Disk for LBT