25 YEARS OF EXPERIMENT IN THE TOOLS FOR SUPERPLASTIC FORMING OF TIALLOYS EVOLUTION OF METALLIC MATERIALS AND DESIGN IN FOUNDRY

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EVOLUTION OF METALLIC MATERIALS AND DESIGN IN FOUNDRY

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Abstract

AUBERT & DUVAL undertook 25 years ago the realization of the first cast tools dedicated to superplastic forming. The experience feedback among our customers and the evolution of technology led us to adapt our offer of alloys intended for the tools, by optimization of existing nuances or the development of specific grades. The programs of studies realized with the French Group of Superplasticity and the collaborations established with Research Centers such as the "Ecole des Mines d'Albi (CROMeP)" or the "University of Nottingham" enabled us to undertake these developments on reliable bases in connection with the industrial conditions of operating. In parallel these collaborations made it possible to make evolve the foundry design of the tools and to approach the aspect of maintenance and repair of tools. This paper will try to make the synthesis of this experiment.

Keywords:
Abaqus® _ Alloys _ Casting _ Foundry _ Modelling _ Mechanical Properties _ Oxidation Resistance _ Refractory _ Steels_ Structure _ Thercast® _ Tools _

1 INTRODUCTION

SPF tooling represents a significant part of the total cost of producing the super-plastically formed part. Careful selection of the material and its manufacturing route is essential in order to obtain the **"right quality at the least cost"** commensurate with the conditions of use.

During 25 years the training of the operating conditions of the tools, the capacity to model them, the best knowledge of the behaviour laws of metallic materials, made it possible to make evolve the choice of the Grades to use and to optimize the Design of the cast tools for tending to this goal.

2 EVOLUTION OF METALLIC MATERIALS

2.1 CONSIDERATIONS OF BASES

Steels and alloys used for the manufacture of SPF tooling are subjected to a wide range of constraints in use, the nature of the stresses encountered depending on the particular thermal cycling involved.

- Thermal gradients during heating and cooling.
- High service temperatures - from up to 950°C for SPF of Titanium alloys (and more for platen press).
- Long times at temperature (2 to 10 hours).
- High pressures (up to 40 bar for diffusion bonding)

Also the materials to be used should therefore be chosen by comparing the conditions of use with their metallurgical properties:

METALLURGICAL PROPERTIES	RELEVANT CRITERIA	
	Length of life	Dimensional stability in service
Yield Stress	x	x
Ultima tensile strength	xx	-
Creep	xxx	xxx
Thermal fatigue	xx	x
Structural stability	x	xx
Oxidation resistance	x(x)	(x)

Table 1, Relation " Metallurgical Properties / Relevant Criteria"

This is why we developed a significant programme of metallurgical characterization of the metallic grades

2.2 SYSTEMATIC PROGRAM OF METALLURGICAL CHARACTERIZATION

To take account of the massivity of SPF tools the characterization is carried out on cast blocks of 200x200x200mm. The figure 1 summarizes the tests.

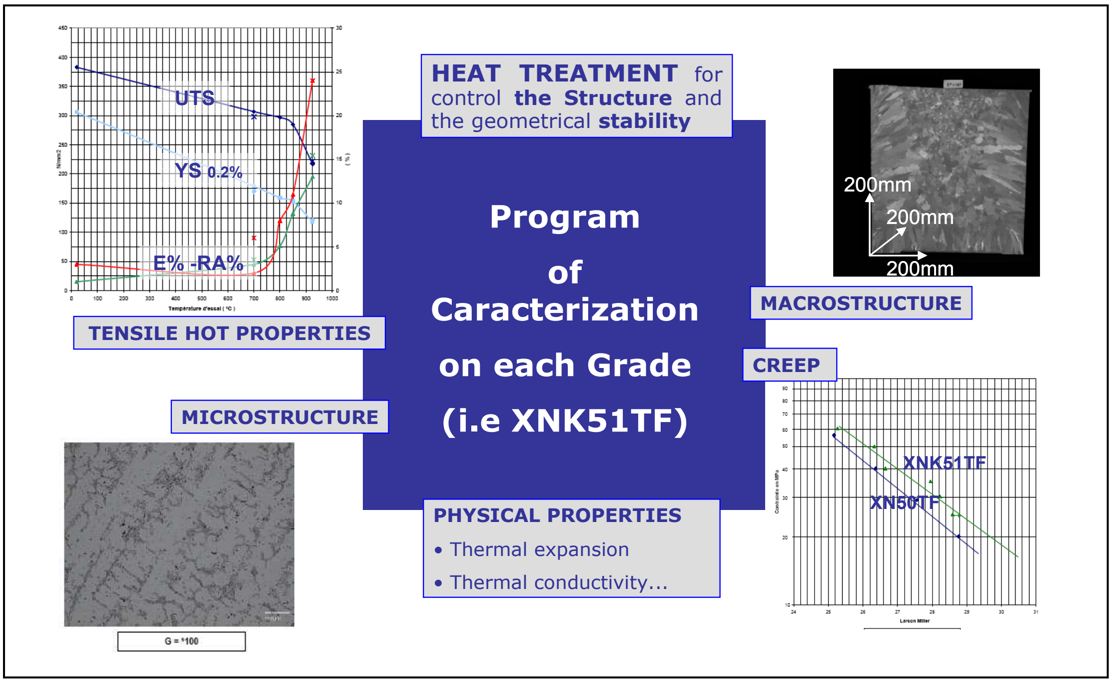


Figure 1, Program of characterization

We also undertook a study of the oxidation resistance of steels and alloys. These tests were carried out at constant temperature (925°C and sometimes 800°C). They do not allow a quantitative evaluation in service where the tools are subjected to cyclic variations of temperature. They give however a good comparison of the behaviour to the oxidation of the various grades.

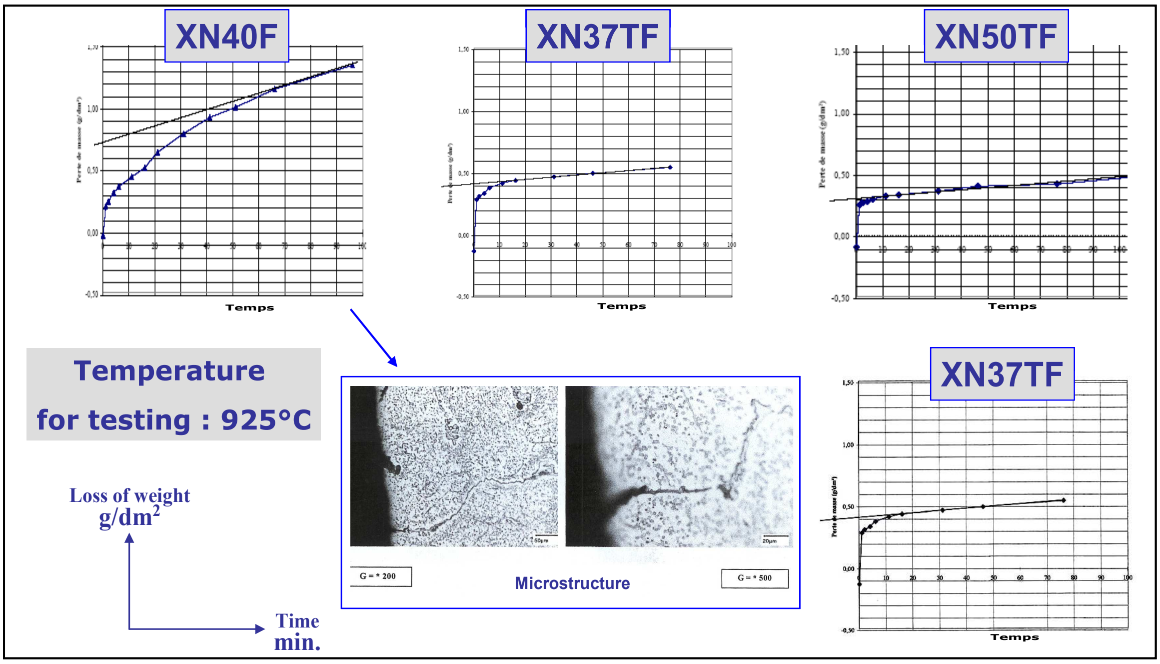


Figure 2, Example of the behaviour to oxidation of 4 grades of steel

2.3 OTHER CRITERIA TO BE CONSIDERED

Other parameters must also be taken into consideration, such as:
Suitability for casting
Machineability prior to service
Weldability before and after service
Reaction between the tooling material and the SP-material or with the «STOP OFF»
Cost

2.4 MAIN GRADES _ CHRONOLOGICAL EVOLUTION

2.4.1 GRADE R2301F (G-X50CRMNNIN 21-9-4)

In the early days of industrial development of the SPF process for titanium, tooling was manufactured from high temperature alloy grades which were commonly available commercially. The risk of the titanium sheet sticking to the surface of the nickel alloys available led to the selection of materials that were as low as possible in nickel content.

AUBERT & DUVAL Grade	COMPOSITION										
	%C	%Fe	%Cr	%Ni	%Co	%Si	Mn	%Mo	%W	Nb	AUTRES %
R 2301 F	0.45	BAL	21.0	4.0	_	0.2	9.0	_	_	_	N : 0.40

Table 2. Chemical analysis of Grade R2301F

After an optimisation of the composition to reduce the risk of segregation and hot cracking, a large number of tools have been cast with reasonable success; however, its lack of oxidation resistance when subjected to temperature (900-950°C) cycling, and its tendency to embrittlement in service due to carbo-nitride precipitation, provoked further work.

2.4.2 Grades XN40F (G-X35NiCr 40-20) _ XN52F (G-X50NiCr 52-18) and XN40SPF (G-X32NiCr 40-25)

The development of “stop-off” coatings prevents any sticking of the titanium to the tool and so allow us to reconsider the use of high nickel alloys.
We did not just try to put into service the standard nickel alloys such as Alloy 800 or 800H, but we considerably altered their compositions to produce the grades designated XN40F, XN52F(for UK market) and more recently XN40SPF.

AUBERT & DUVAL Grade	COMPOSITION										
	%C	%Fe	%Cr	%Ni	%Co	%Si	Mn	%Mo	%W	Nb	AUTRES %
X.N 40 F	0.35	BAL	20	40.0	_	1.35	1.0	_	_	<0,30	_
X.N 52 F	0.5	BAL	18.5	52.0	_	1.6	1.0	_	1.0	_	_
X.N 40 S.P.F	0.33	BAL	24.5	40.0	_	1.35	1.0	_	_	0.30	_

Table 3 Chemical analysis of Grade XN40F, XN52F and XN40SPF

- The high carbon content produces carbides which give the alloy good creep properties.
- The increased chromium level improves oxidation resistance even in the areas where inevitably some segregation will have taken place. XN40SPF goes even further in this direction so that it is chosen where the tool has particularly thick sections that cannot be designed out.
- The chemical balance is designed to produce a largely austenitic structure but without any risk of embrittlement by sigma phase (a well known problem in Cr25/Ni20 steels).
- A small quantity of Niobium or Tungsten is added to control carbide distribution and to give a better performance at temperature than either historical wrought 800/800H alloys.

• XN40F, XN52F and XN40SPF are widely used in industry in Europe for production of SPF tooling.

2.4.3 Grades XN37TF (G-X30NiCrW 35-25-4) and XN50TF (G-X50NiCrW 50-27-5)

Work carried out by the French Superplasticity Group at the “Ecole des Mines d’Albi”, has demonstrated the good fatigue and creep behaviour of these alloys, but it has also shown their limitations as regards high stress situations resulting from the working cycle (SPF-DB) or from the geometry of the parts (stress concentrations). They also highlighted the beneficial role of Tungsten.

AUBERT & DUVAL Grade	COMPOSITION										
	%C	%Fe	%Cr	%Ni	%Co	%Si	Mn	%Mo	%W	Nb	AUTRES %
X.N 37 T.F	0.30	BAL	25.0	36.0	_	1.40	1.0	_	4.0	0.5	_
X.N 50 T.F	0.50	BAL	27.0	50.0	_	1.20	1.0	_	5.0	_	_

Table 4. Chemical analysis of Grade XN37TF and XN50TF

-The grades XN37TF and XN50TF were developed to deal with this situation, whilst being designed along the same lines as the XN40/XN52 grades.

-In XN50TF, the improved hot strength due to the increased tungsten content is in addition to the increased oxidation resistance resulting from a higher content of chromium (27%). To balance the structural concerns, the nickel level needs to be 50%. This means that it is a grade that is somewhat more complicated to produce, and thus is reserved for high volume production or high stress situations.

- XN50TF is used for SPF-DB tooling and XN37TF for press platens owing to their high hot strength and oxidation resistance.

2.4.4 GRADES PER101F (G-NI-CO14 CR10 MO3 AL TI) AND XNK51TF (G-NI-CR27 CO14 W5)

The alloy PER101F possesses exceptional hot strength up to 1100ºC..This alloy is very well suited to applications such as tooling for SPF/DB of superalloys and titanium where a very high dimensional stability is required.

AUBERT & DUVAL Grade	COMPOSITION										
	%C	%Fe	%Cr	%Ni	%Co	%Si	Mn	%Mo	%W	Nb	AUTRES %
P.E.R 101 F	0.20	—	10.0	BASE	14.0	—	—	3.0	—	—	Ti, Al, Zr, V, B

Table 5, Chemical analysis of Grade XN37TF and XN50TF

This Nickel base alloy PER101F contains only a limited amount of chromium and so some precautions against oxidation at temperature are advisable. The composition with Aluminium and Titanium additions requires vacuum melting. The machining is not easy.

- PER 101F is used for SF-DB tooling dedicated to engine- blades for exemple.

The alloy XNK51TF is an evolution from XN50TF with a limited substitution of Nickel by Cobalt.

AUBERT & DUVAL Grade	COMPOSITION										
	%C	%Fe	%Cr	%Ni	%Co	%Si	Mn	%Mo	%W	Nb	AUTRES %
X.N 50 T.F	0.50	BAL	27.0	50.0	—	1.20	1.0	—	5.0	—	—
X.N.K 51 T.F	0.50	BAL	27.0	36.0	14.0	1.20	1.0	—	5.0	—	

Table 6, Comparison of Chemical analysis of Grades of XNK51TF and XN50TF

The Main properties of this alloy are as following *(See figure 4 and table 8 in the paragraph 2.5)*:
- The mechanical behaviour at high temperature is intermediate between both XN50TF and PER101F
- The oxidation resistance is very good as well as XN50TF
- The acquisition price of material and the machining cost are lower than the PER101F

2.4.5 GRADE X26NCBF (G-X30CRNIMNNBN 25-12)

- The grade X26NCbF has been developed for the 750/850°C working range of new Titanium SPF alloys, such as "SP700" or very fine grain TA6V.

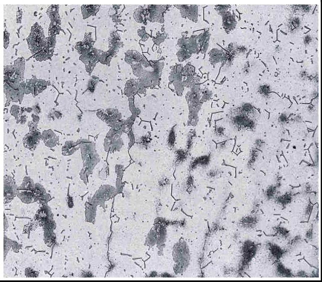
AUBERT & DUVAL Grade	COMPOSITION										
	%C	%Fe	%Cr	%Ni	%Co	%Si	Mn	%Mo	%W	Nb	AUTRES %
X 26 N.Cb.F	0.30	BAL	26.0	12.0	—	—	5.0	—	—	2.0	N : 0.60

Table 7, Chemical analysis of Grade X26NCbF

- In this temperature range, the mechanical properties (tensile and creep) and oxidation resistance of X26NCbF are very high.
- In comparison with 25%Cr-20%Ni steels, the structural stability is much improved.
- In comparison with 36-40%Ni alloys, used for SPF of traditional titanium grades (at 925°C), X26NCbF is cheaper; despite its lower nickel content this grade exhibits satisfactory thermal shock resistance .
- In comparison with 21%Cr-9%Mn-4%Ni steel, the scaling resistance (in oxidation) is better and X26NCbF is easier to machine.

The following criteria were to be considered:

- Iron-base alloy with minimum Nickel content for low cost
- 25% chromium to give good oxidation resistance
- Restricted carbon levels to prevent large carbides
- Addition of Manganese and Nitrogen to ensure an austenitic matrix at all temperatures and prevent sigma phase formation
- Introduction of Niobium to form nitrides to reinforce the austenitic matrix
- Obtain as near as possible an eutetic composition to give good niobium nitride dispersion



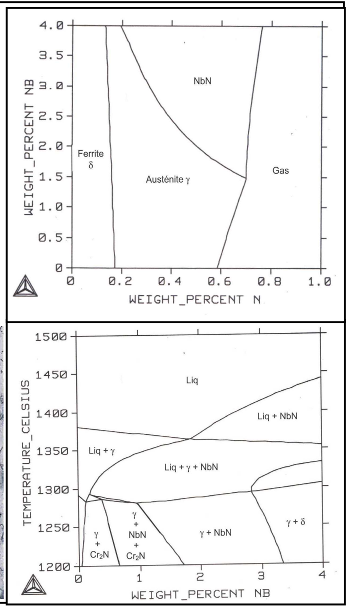


Figure 3, For the design of this steel, the THERMOCALC simulation has been used

2.5 MAIN GRADES COMPARISON OF THE HIGH-TEMPERATURE PROPERTIES

The table 8 and the figure 4 summarize and compare the mechanical properties and the oxidation resistance of the nuances previously described.

NUANCES AUBERT & DUVAL	20°C TENSILE PROPERTIES UTS (MPa)	20°C TENSILE PROPERTIES YS0.2 (MPa)	20°C TENSILE PROPERTIES E%	850°C TENSILE PROPERTIES UTS (MPa)	850°C TENSILE PROPERTIES YS0.2 (MPa)	850°C TENSILE PROPERTIES E%	850°C CREEP RUPTURE - MPa 10h	850°C CREEP RUPTURE - MPa 100h	850°C CREEP RUPTURE - MPa 1000h
X 26 N.Cb.F	560	420	2.5	270	175	18	-	79	50

NUANCES AUBERT & DUVAL	20°C TENSILE PROPERTIES UTS (MPa)	20°C TENSILE PROPERTIES YS0.2 (MPa)	20°C TENSILE PROPERTIES E%	925°C TENSILE PROPERTIES UTS (MPa)	925°C TENSILE PROPERTIES YS0.2 (MPa)	925°C TENSILE PROPERTIES E%	925°C CREEP RUPTURE - MPa 10h	925°C CREEP RUPTURE - MPa 100h	925°C CREEP RUPTURE - MPa 1000h	925°C CREEP ELONGATION for 1% In 100h	925°C CREEP ELONGATION for 1% In 1000h
R 2301 F	1100	700	9	205	120	25	66	45	25	30	-
X.N 40 S.P.F	335	220	2	140	77	35	45	34	26	-	20
X.N 52 F	380	225	2	165	80	37	50	33	24	-	19
X.N 37 T.F	325	310	1.1	200	120	8	-	-	27	-	23
X.N 50 T.F	373	259	2	157	123	17.5	85	40	29	-	22
X.N.K 51 T.F	382	295	2	215	125	15	-	45	36	-	27
PER 101 F	680	640	4	655	410	8	-	200	130	160	>100

Table 8, Mechanical properties

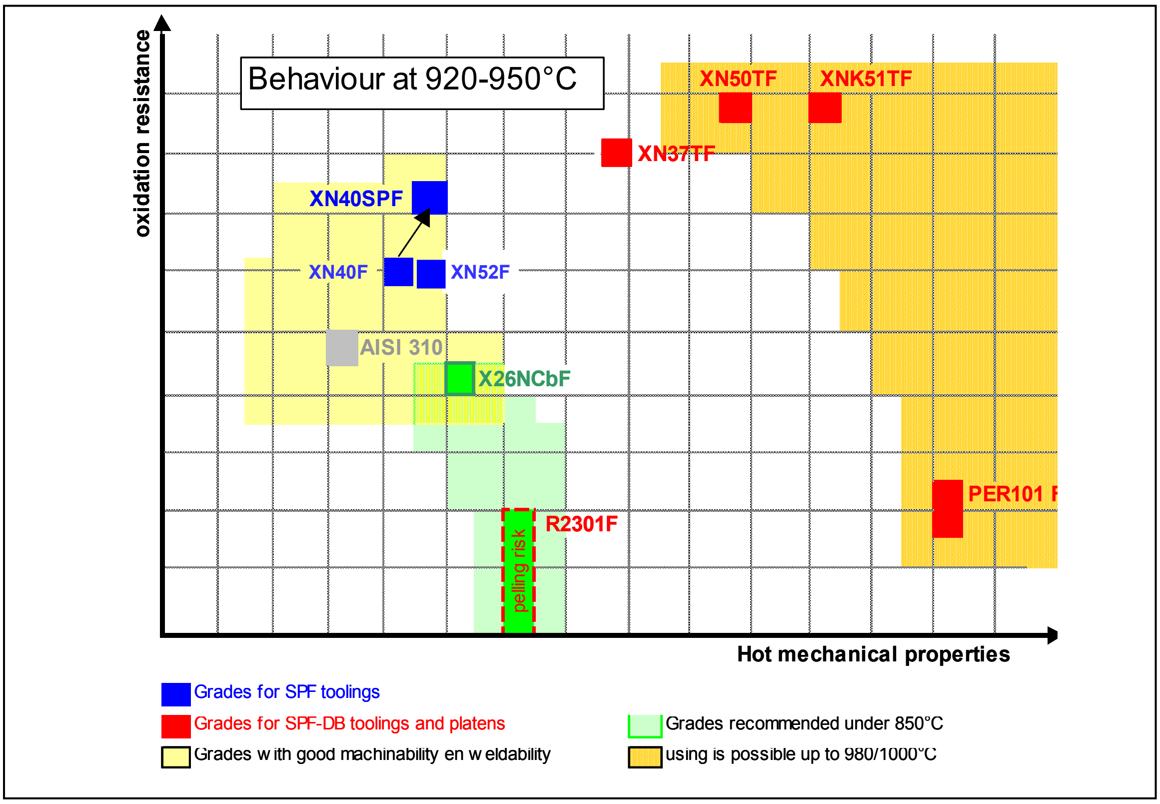


Figure 4 , Relative location of the grades according to the hot properties and to the oxidation resistance

2.6 MAIN GRADES _ COMPARISON OF USING PROPERTIES

AUBERT & DUVAL Grade	Maximal TEMPERATURE recommended	USING PROPERTIES			
		OXIDATION RESISTANCE	MACHINABILITY	WELDABILITY	COST
X.26 N.Cb.F	850°C recommandé 925°C possible	XXX	XXX	XX(X)	X
R 2301 F	850°C recommended* 925°C possible	XX	XXX	XX(X)/X ***	X(X)
X.N 40 S.P.F	950°C	XXX(X)	XXX(X)	XXX(X)	XX
X.N 52 F	950°C	XXX	XXX	XX(X)	XX(X)
X.N 37 T.F	950°C	XXX(X)	XX(X)	XX(X)	XX (X)
X.N 50 T.F	980°C	XXX (X)	XX	XX	XXX
X.N.K 51 T.F	1050°C	XXX (X)	XX	XX	XXX (X)
P.E.R 101 F	1100°C **	X	X (1) X (X) (2)	X	XXXX(X) (1) XXXXX (2)

* for oxidation behaviour
**for mechanical properties only
*** new /used material
(1) : only stabilised condition
(2) : with spécial Heat

Table 9, Using properties of grades

2.7 MAIN GRADES _ MAIN APPLICATIONS

According to the properties of the various grades it is possible to determine the most favourable applications depending from the working temperature (900/ 950°C or 700-850°C), the working pressure and the dimensional stability (SPF or SPF-DB) and also the kind of tool: mould or platen of press.

GRADES AUBERT & DUVAL	Ti-SPF TOOLINGS	Ti-SPF & SPF-DB TOOLINGS	PLATEN of PRESS for Ti	- SPF TOOLINGS for Ti-SP700 material - HOT FORMING TOOLINGS
X 26 N.Cb.F	(X)	(X)	X hot forming	X
R 2301 F	X	X	X hot forming	X
X.N 40 S.P.F	X			X
X.N 52 F	X			
X.N 37 T.F			X SPF	
X.N 50 T.F	X	X		
X.N.K 51 T.F		X	X SPF(DB)	
P.E.R 101 F	X	X		

Table 10, Main applications of grades

3 EVOLUTION OF DESIGN IN FOUNDRY

However well we optimise the chemical compositions of the tools, the laws of solidification mean that thick sections always accentuate the risk of segregation and lack of metal soundness. Thus areas of the casting are produced where preferential degradation of the tool will occur. In order to combat this, it is necessary to increase the size of the risers used to feed the part during solidification, and this can dramatically increase the weight of metal poured; the result is poorer economics and difficulties in the manufacturing process. Another way to improve this situation is to reduce the wall thickness of the tools; in this way we can improve soundness, minimise segregation and produce a finer structure. The development of alloys with improved mechanical properties at temperature (e.g. X26NCbF) means that such an approach is now possible. The design of tools with thin walled areas means that we have to also design into the tool some ribs to maintain rigidity.

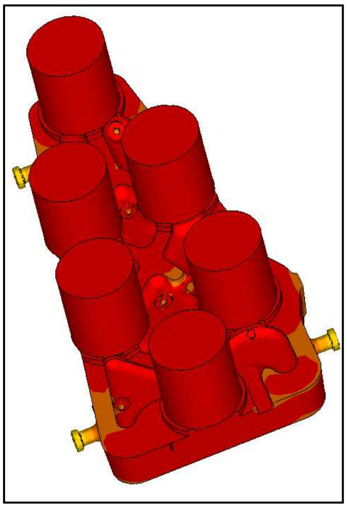


Fig 5 : Risers on large Tool (2500x1500mm)

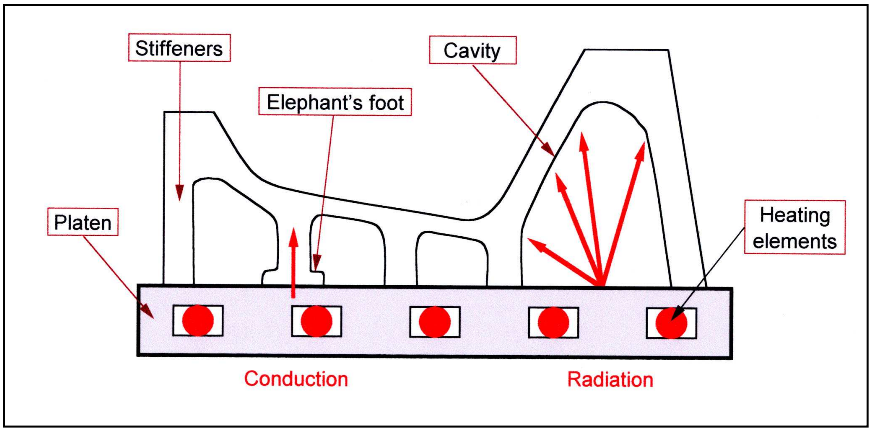


Figure 6 : Design of toll / thermal effects

Sometimes, this type of design has come up against pre-conceived ideas concerning the heat transmission from the platen to the tool. The smaller contact area due to the cavities compared to a flat-backed casting has worried designers who fear insufficient or non-uniform heat transfer.

Development of these thin walled tools with ribs has generated more complexity for the foundry producing the castings, as there is a potential for problems due to hot spots at the intersections of the stiffening ribs. In these cases, computer modelling of the casting process, already extremely useful for large castings, becomes essential. A programme called **THERCAST**, developed jointly by the Ecole de Mines de Paris and several industrial companies including Aubert et Duval, is used by the foundry to define the details of the different phases of production of a casting, namely:
- simulation of the filling of the mould
- simulation of solidification and cooling

With **THERCAST** we can determine in advance the areas that will solidify last, these areas being the ones with the greatest risk of lack of soundness due to contraction of the metal during solidification. The foundry can thus modify the design of the runner and riser system to optimise the integrity of the final casting.

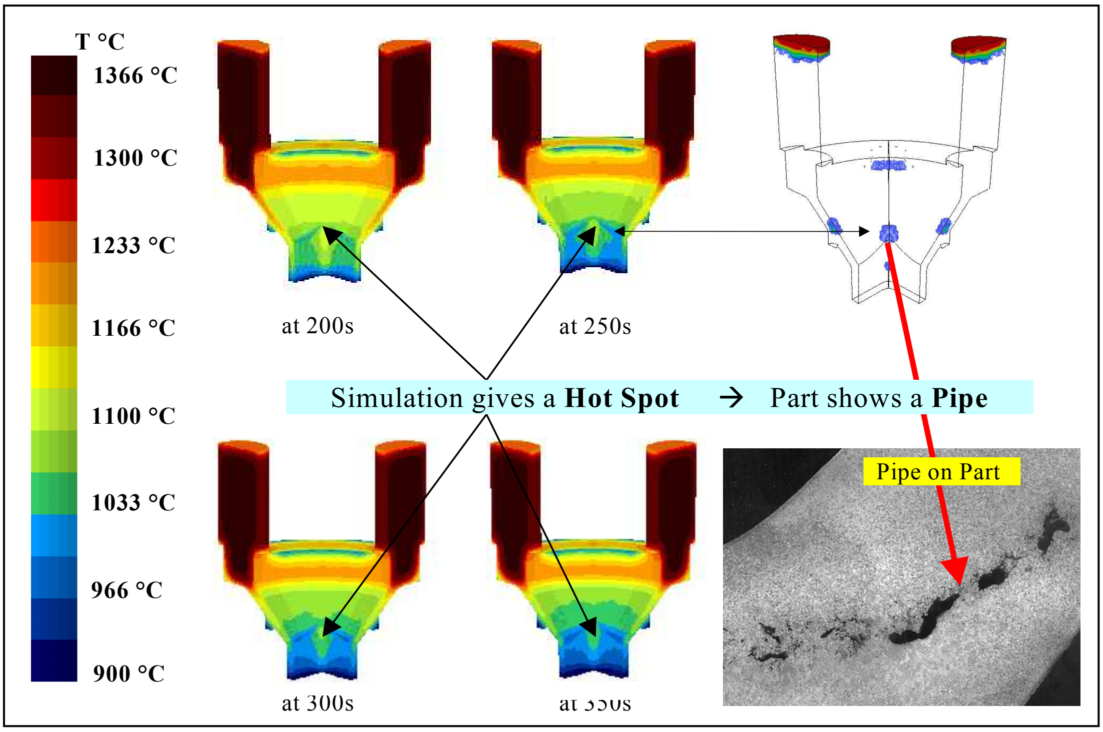


Figure 7 : Using THERMOCAST to assess the defect risk

Thermo-mechanical modelling of the casting process also allows us to evaluate the stresses and distortion produced during solidification and cooling. If the design cannot be changed to accommodate the proposed modifications to eliminate the problem areas, at least it allows the foundry to increase the controls and checks in these critical areas. It is also possible to incorporate local inserts into the moulds to give different cooling rates in specified areas (e.g. chills, different sand compositions etc).

4 CONCLUSION

- The development of superplastic forming of titanium alloys requires optimisation of the process parameters, especially as regards the cost of the tooling as this represents a significant part of the overall cost.
- Unsatisfactory service life of the platens or tools themselves (be it too short a life, or use of expensive materials giving an unnecessarily luxurious solution) is thus to be avoided.
- An extensive range of material options is therefore necessary, these materials possessing reproducible and well-documented metallurgical properties.
- A systematic property evaluation programme (including mechanical properties and oxidation behaviour) was carried out.
- From this, a comprehensive range of alloys was developed, either based on existing grades or by the invention of new grades.
- The production conditions in the foundry are largely controlled by modelling; in this way optimisation of the geometry and soundness of the castings is achieved, giving reliable metallurgical properties in the base metal.

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