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Developments in Design and Materials for Cast SPF Tooling

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Large titanium and aluminum sheet parts can now be formed into very complex assemblies by the process of superplastic forming. This has resulted in the need for major work to develop new alloys, new design methods and new manufacturing routes to ensure the production of high quality tooling. 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. For many years the optimization of the alloy composition, the melting and casting foundry techniques and the design of the tools was done in a semi-empirical way, being largely based on practical experience. This method meant that the development was slow and unwieldy, and therefore, not compatible with the rapidly changing constraints of the SPF industry today. The fact that extremely powerful modelling programmes such as ThermoCalc and DICTRA are available for the design of new alloys, or Thercast for the optimization of the foundry melting and processing, makes it possible to introduce innovative techniques faster and with more immediate certitude as to their success. Thus, the casting process has become the most competitive and appropriate method of manufacture of the high performance tools in use today. This paper will discuss how these current technologies have been developed, and coupled with the experiences in the foundry, have assisted in the production of new materials, that optimize the tooling required in SPF operations.

Keywords superplastic forming, ThermoCalc+DICTRA modeling, tooling materials

1. History

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. The alloy 22-4-9 (22% Cr, 4% Ni and 9% Mn) was initially selected because it performs satisfactorily as a tooling material for hot forming of titanium at lower temperatures (700-760 °C). This steel had originally been developed as an exhaust valve material for automobiles (grade SAE EV8) and had been produced in the form of rod coil. To manufacture tooling, the casting process was employed, thus giving better dimensional stability to the tool and allowing the production of large tooling at a minimum cost.

With the development of SPF, the demand for larger and larger tools soon showed that this grade was subject to segregation and hot cracking, and it was necessary to adjust the composition to optimise its performance in its new role (Fig. 1).

This experience led to the study of the SPF process and the tooling related to it along three principal lines of approach:

- The development of grades appropriate not only to the service conditions but also to the manufacturing route.
- Optimising the tool geometry, to give as thin a section as possible to ensure good casting soundness.
- Making the details of the mechanical properties (especially the properties at temperature) available to the end user. Previously, data from the literature was related to small cast test pieces or thin sections; this data needed to be modified to account for the effect these heavy and relatively thick-walled parts have on the metallurgical structure.

This work was carried out in conjunction with the companies actually performing the super-plastic forming, in order to take into account the material and design criteria, and the mechanical and thermal behaviour required. Tests were performed in our own laboratories, as well as in the French Superplasticity Group (made up of industrialists and university research groups) and in consultation with establishments in other countries (such as Nottingham University).

2. Initial Development of New Grades

In the first instance, research concentrated on adapting existing materials. Thus, the improvement from the standard 22-4-9 was obtained by studying the casting of ingots for the

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valve steel coil, and also reviewing the solidification behaviour of the grade using DTA (Differential Thermal Analysis).

Better carbon/nitrogen balance, a readjustment of the austenite and ferrite forming elements, and rigorous control of residual elements produced a better combination of the properties required, i.e., reduced sensitivity to hot cracking, good nitrogen solubility during solidification and a finer structure (Table 1). This grade, designated *R2301F*, is better adapted to the requirements of cast tools with relatively massive sections (Fig. 2).

A large number of tools have been cast in this grade with reasonable success; however, its lack of oxidation resistance when subjected to temperature cycling, and its tendency to embrittlement in service due to carbo-nitride precipitation, provoked further work. In fact, the properties of steels with large concentrations of nitrogen and manganese are not ideally suited to the requirements of current SPF technology (Ref 1).

The next phase of the study was facilitated by the development of “stop-off” coatings on the tools. These coatings prevent any sticking of the titanium to the tool and so allow us to reconsider the use of high nickel alloys. Bolstered by experience in adjusting the 22-4-9, the standard nickel alloys such as Alloy 800 or 800H were not put into service as is, but the compositions were considerably altered to produce the grades designated *XN40F* and more recently *XN40SPF* (Table 2) (Ref 2).

In *XN40F*, the high carbon content produces carbides, which give the alloy good creep resistance. 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 25/20 steels, AISI 310) (Fig. 3).

To facilitate the casting process, additions of aluminium and titanium, present in wrought Alloy 800 and 800H, were not permitted. Niobium was, however, added to control carbide distribution and to give both *XN40F* and *XN40SPF* a better performance at temperature than either of the two previous alloys.

Fig. 1 Typical structure in a 200 mm cube used for property evaluation. This micrograph is XN50 TF

Table 1 Chemical composition of initial grade and optimized cast grade

	C	N	Si	S	P	Mn	Cr	Ni
SAE EV8	0.48	0.38	–	–	–	8	20	3.25
(UNS S 63008)	0.58	0.55	<0.25	<0.030	<0.050	10	24	4.50
R2301F	0.35	0.30	–	–	–	8.0	21.0	3.5
	0.45	0.45	0.40	<0.005	<0.025	9.0	22.0	4.0

Table 2 Chemical composition of «800» type alloys and optimized cast grades

	C	Si	S	P	Mn	Cr	Ni	Other
Alloy 800	–	–	–	–	–	19.0	30.0	+Al
(UNS N08800)	0.10							
Alloy 800H	0.05	<1.0	<0.015	<0.045	<1.5	23.0	35.0	+Ti
(UNS N08810)	0.10							
XN40F	0.32	1.0	–	–	0.8	19.0	38.0	+Nb
	0.42	1.6	<0.005	<0.025	1.4	23.0	42.0	
XN40SPF	0.30	1.0	–	–	0.8	23.0	38.0	+Nb
	0.40	1.6	<0.005	<0.025	1.4	26.0	42.0	

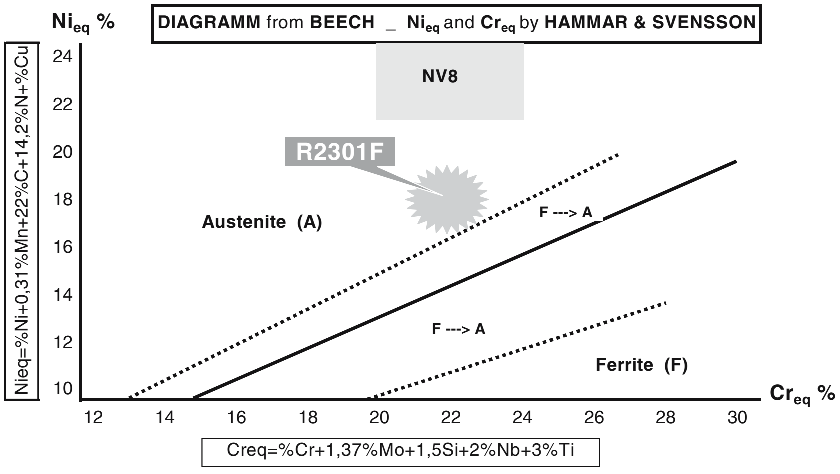


Fig. 2 Modification of composition from initial grade to optimized cast grade

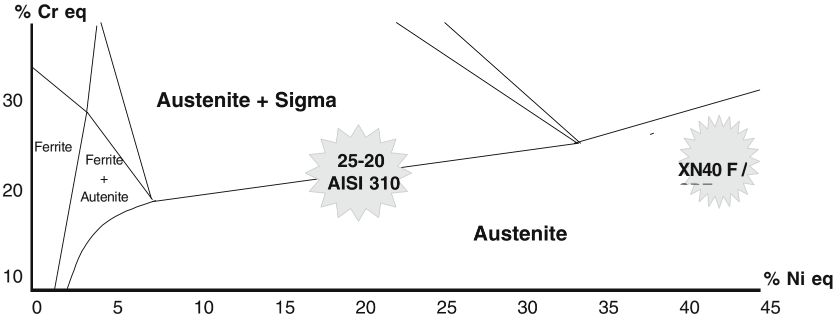


Fig. 3 Tendency to sigma phase precipitation in relation to matrix composition at 800 °C

Table 3 Chemical composition and mechanical properties (at 925 °C)

	Nominal composition							Properties at 925 °C	
	C	Si	Mn	Cr	Ni	Nb	W	UTS/YS 0.2%, MPa	Rupture stress, MPa 1000 h
XN40SPF	0.33	1.35	1.0	24.5	40	+	–	140/77	26
XN37TF	0.30	1.4	1.0	25	36	+	5	200/120	27
XN50 TF	0.50	1.2	1.0	27	50	–	4	157/123	29

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

Work carried out by the French Superplasticity Group at the Ecole des Mines, Albi, has demonstrated the good fatigue and creep behaviour of these alloys, but it has also shown their limitations as regards to 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.

The grades *XN37TF* and *XN50TF* were developed to deal with this situation, whilst being designed along the same lines as the XN40 grades (Ref 3). 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 %) (Table 3). 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.

Dilatometer work was carried out on all these grades to define the heat treatments required in order to relax the stresses caused by cooling after solidification of the casting, and to ensure a stable structure that would not cause further problems by producing any movement in service (Ref 4). If this initial heat treatment is not carried out on these grades containing high levels of carbides, it is possible to get contraction during service due to continual slow precipitation taking place (Fig. 4).

XN37TF and XN50TF are used for tooling and for press platens owing to their high hot strength and oxidation resistance.

2.1 Current Work on the Development of New Grades

The development of improved grades of tooling alloy was thus taking place progressively, and at the same time, the companies carrying out SPF were fine-tuning their requirements for the tooling. This approach requires extensive experimentation (i.e. trial casts, phase studies by micro-analysis, x-ray diffraction, etc.), which is not compatible with rapid and economical development (Ref 5). Also, the search for materials with totally new properties does not lend itself to this iterative process. Prediction of phases that will be present by thermodynamic simulation has allowed us to be more precise and develop more quickly compared to the older methods using empirical diagrams such as Schaeffler, Price, Beech, Suutala, etc.

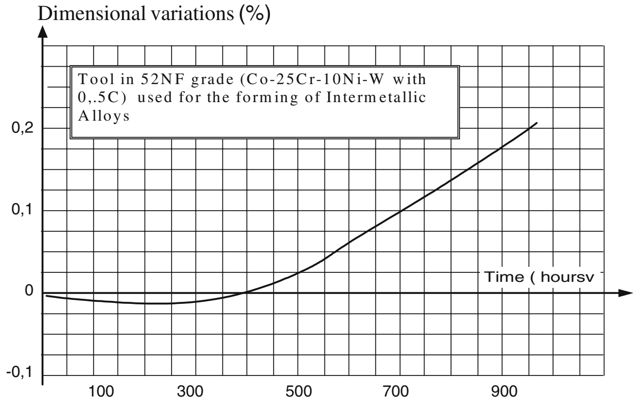


Fig. 4 Typical dimensional variation (1050 °C under 10 MPa Stress) of unstabilized alloy

Computer aided design of alloys using *ThermoCalc*, which is based on continually changing thermodynamic data, produces equilibrium diagrams and quantitative data which then define the quantity and composition of individual phases as a function of the composition and temperature (Fig. 5). Of course, limited experimentation is still required in order to calibrate the computer model and to complete areas where the data is still imperfect or missing. However, as more and more data becomes available, the amount of experimentation required is reduced, and the computerised system becomes more powerful. Calibration will also be required to take account of real working conditions of the tooling, since

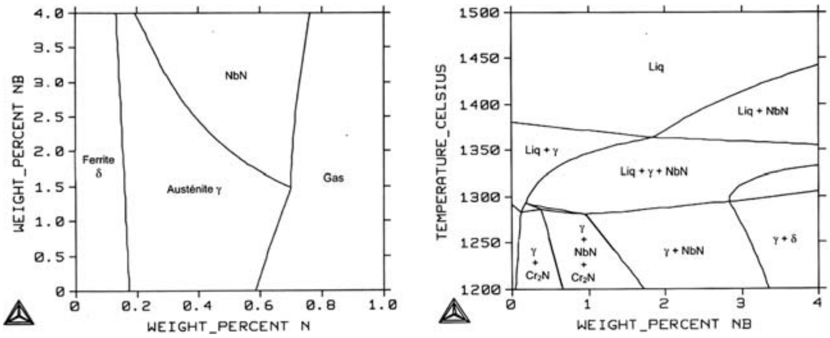


Fig. 5 ThermoCalc Diagram

Table 4 Chemical composition deduced from THERMO-CALC

Elements	C	Mn	Cr	Ni	Si	N	Nb
% Mass	0.3	5	25	12	0.30	0.55	2

equilibrium conditions are rarely fully attained. Here, the practical experience of the user of the program will remain an essential part of the process until modelling techniques that include kinetic phase transformation become available. Certain programmes such as *DICTRA* are already becoming available with this aim in view.

ThermoCalc has been used to design a tooling alloy for SPF intended for use at 700-850 °C, this being the temperature range for a new series of titanium alloys currently being developed (Ref 6). The objective of the exercise was to produce an alloy that exhibited the best combination of mechanical properties and oxidation resistance in this limited temperature range in order to reduce in-service costs. It was also necessary to minimise the cost of the alloy and casting manufacture, thereby, lowering alloy content in terms of the expensive elements was required, along with attaining good castability. This meant that the following criteria had to be considered:

- Fe-base alloy with minimum Ni content
- 25% Cr to give good oxidation resistance
- Restricted C level to prevent large carbides
- Mn and N to ensure an austenitic matrix at all temperatures, and thus, prevent sigma phase formation or the appearance of ferrite
- Nb to form nitrides to reinforce the austenitic matrix
- Obtain as near as possible a eutectic composition to give good Nb nitride dispersion.

Use of *ThermoCalc* meant that the composition could be clearly defined (Table 4), in particular the N level, as it is essential that the N remains in solution during solidification and to obtain the eutectic composition γ-Nb (C, N).

Thermodynamic modelling also predicts the composition and quantity of each phase present (Fig. 6). Thus, at 850 °C, which is the maximum temperature envisaged for use of this grade, the austenite will contain 22.5% Cr, thereby, ensuring good oxidation resistance. The molar fraction of hardening phases (nitrides and, to a lesser extent, carbides) is around 10%, which is ideal for the mechanical properties.

A 200 mm cube of this alloy was cast to verify that the model predicted accurate results and to make a full assessment of the properties obtained. The results are given below and fall well in line with predictions and objectives, especially in relation to the creep properties at 850 °C, which are equivalent to 35Cr/25Ni/Cb steel. This alloy is now known as X26NCbF.

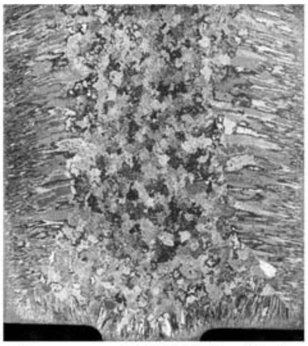
2.2 Optimisation of the Design of the Castings

However well the chemical compositions are optimized, 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, resulting in poorer economics and difficulties in the manufacturing process (Fig. 7).

Another way to improve this situation is to reduce the wall thickness of the tools. In this way the soundness can be improved while minimizing segregation and producing 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 the tool must be designed with some ribs to maintain rigidity.

Sometimes, this type of design has come up against preconceived ideas concerning the heat transmission from the platen to the tool (Fig. 8). 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.

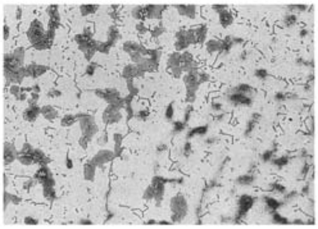
Modelling with *ABAQUS* has shown that in the range of service temperatures used (700-925 °C), the heat conduction from the platen is substituted by radiation across the cavities to a very large extent. If a different balance between conduction and radiation is required, the shape of the base of the stiffeners can be altered into what are commonly known as "elephant's feet", thus increasing the surface area of contact. This also helps to reduce the pressure on specific areas of the platen, thus, reducing "marking", or deformation, of the platen after long times at temperature. This is particularly relevant for ceramic platens which are more brittle and sensitive to local pressures—in fact it is always a good idea to design the cavities such that there are no high pressure points on the corners of the ceramic blocks, as this could lead to cracking away of these corners.



Macrostructure of 200x200x200mm block

Values at 850°C	
UTS	272 MPa
YS 0.2%	175 MPa
E	17.8 %
Creep-rupture in 1000 h	50 MPa

Chemical analysis			
C	0.291	**Ni**	12.08
Si	0.30	**Cr**	25.48
Mn	4.83	**Nb**	2.11
S	0.005	**N2**	0.564
P	0.014	**Fe**	Bal.



Micrograph of stress relieved block
X 50

Fig. 6 Thermodynamically designed grade X26NCbF (Cr25-Ni12-Mn5-Cb2-N)

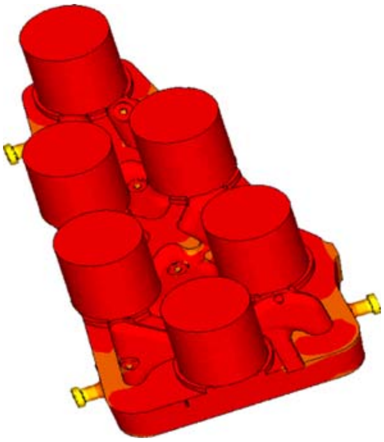


Fig. 7 Risers on large tool (2500 × 1500 mm)

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* the areas that will solidify last can be determined in advance, 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

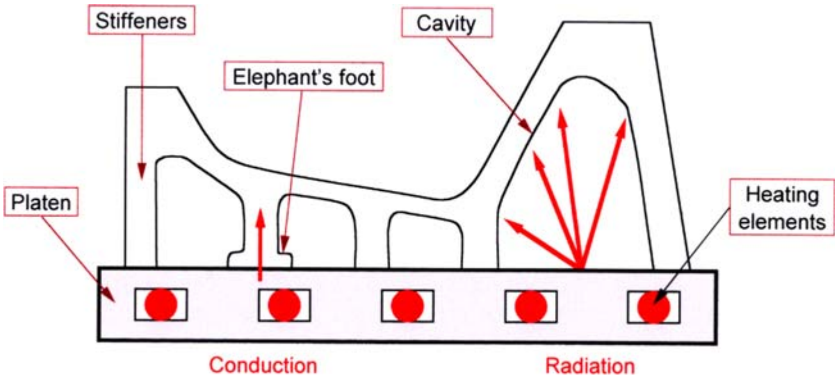


Fig. 8 Design of tool/thermal effects

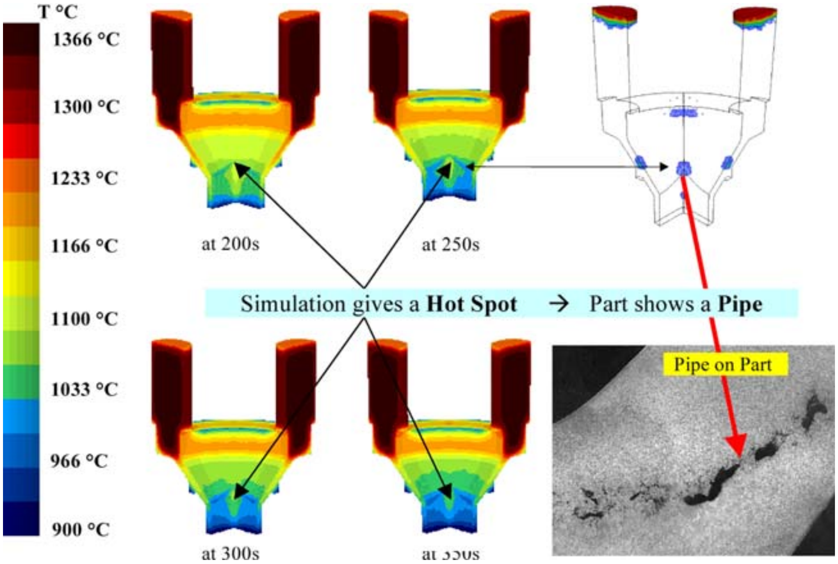


Fig. 9 Using *ThermoCast* to assess the defect risk

the design of the runner and riser system in order to optimise the integrity of the final casting.

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, the opportunity to control and check these critical areas (Fig. 9). 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.).

3. Conclusion

In this article, the ways in which computer modelling can be used to optimise the quality and properties of cast SPF tooling has been illustrated; this optimisation takes the form of improving the soundness of the metal itself and developing alloys with higher mechanical and oxidation resistant properties. This necessitates a close dialogue between the foundry, the SPF process user and the metallurgist. These computerised tools are increasingly powerful but still rely on the experience and competence of those using them.

Their use also depends on the availability of data that is reliable and relevant to the types of tools being manufactured, rather than standard bibliographic information. The need for this information in order to use these powerful computer programmes made us realise that our customers also need this type of data in order to design their SPF/DB tools. Consequently, extensive testing of representative cast pieces has been carried out in order to produce a detailed data bank of properties that can be used by SPF tool designers in their calculations for designing SPF tools.

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