RESIDUAL STRESS MODELLING DURING THE OIL QUENCHING

OF AN ASTROLOY TURBINE DISK.

J.M.FRANCHET*, F.DEVY***, P.E.MOSSER   *

Y.HONNORAT**, A.BENALLAL   ***

* Materials and Processes Lab.,SNECMA-BP48,92234 GENNEVILLIERS
** Materials and Processes Lab.,SNECMA-BP81,91003 EVRY
*** LMT ENS-CACHAN, 61 av. du président WILSON,92235 CACHAN

FRANCE

ABSTRACT

Nickel base powder metallurgy disks acquire their final strength during the heat treatment. The quench after solution is particularly critical as the cooling rate must be rapid enough in order to precipitate fine γ' particules and thus to get the desired properties; nevertheless aggressive heat extraction can lead to quench cracking or at least to the development of very high residual stresses.

In order to optimize the quenching, i.e. both to get a sufficient cooling rate and to avoid too high residual stresses, SNECMA has developed in cooperation with LMT a model for disk quenching which describes the generation of residual stresses during the cooling.

A precise prediction of temperature evolution during the quench is a prerequisite to stress calculation.

The main difficulty is the identification of the material behaviour. The dilatometric curve takes into account the shrinkage due to the start of the γ' precipitation. The thermomechanical behaviour is determined as pseudoplastic at high temperature and elastoplastic at low temperature. It was determined both in tension and compression, as a preliminary study showed that a compressive state was prevalent in the disk during quenching. Altogether the effect of γ' precipitates on this behaviour has been determined.

Finally, these results were implemented in the finite element code SAMCEF-VISCO to calculate the stress generation in a large turbine disk. A complete correlation between experimentation and calculation is performed, including temperature rate prediction, disk bore and rim displacement and final stresses. The agreement between the two sets of results shows the consistency of the adopted approach.
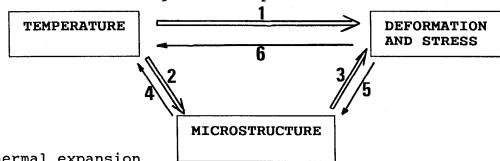
INTRODUCTION

Nickel-base powder metallurgy disks acquire their final resistance during the heat treatment. The quench after solution is particularly critical, as in order to get the desired properties associated with a fine γ' precipitation, an energetic quenchant, such as oil, is to be used for the large disks. The quench modelling will address the three difficulties of this process:

- will the cooling be sufficient to meet the mechanical specifications?
- will the surface stresses during cooling remain at a low enough level to avoid quench cracking?
- are the residual stresses induced by the deformation under the thermal gradient controllable at an acceptable level?

This paper will focus on stress generation, assuming the cooling rate prediction is an available method.

PREDICTING THE STRESSES DEVELOPED DURING THE QUENCH

The basic mechanism for developing the stresses during the quench is the differential expansion between the cold surface material and the hot inner material. Two expansion mechanisms are to be taken into account: classical thermal expansion and precipitation-induced shrinkage. The material accomodates this differential expansion through different mechanisms continuously varying with the temperature. At low temperature the behaviour is classically elastoplastic. The yield stress appears to depend on the secondary γ' size. At high temperature, it is purely pseudoplastic. Thus the behaviour evolution is governed by two parameters also: (1)-softening and change in mechanisms as the temperature increases; (2)-variation of yield stress with γ' morphology. The coupling scheme between temperature, material response and stress generation is shown in Fig.1. It has already been demonstrated that this coupling is very strong during the quench of martensitic steel [1]. This paper will show how some retroaction effects can be neglected for Ni-base alloys so that the stress prediction can be considered as a straight forward procedure from temperature calculation to stress generation prediction.

1. thermal expansion
2. microstructural transformation
3. precipitation-induced shrinkage, precipitation hardening, tranformation-induced plasticity
4. latent heat
5. stress induced precipitation
6. viscous power dissipation

Fig.1: Completely coupled formulation of quench modelling

METALLURGICAL BEHAVIOUR OF ASTROLOY DURING THE QUENCH

The classical solutionning condition of Astroloy is 1100°C/4h. The starting microstructure is an almost fully recrystallized γ, with grain growth blocked by intergranular primary γ' (amount : 10-15%). The typical cooling-rate windows for an oil-quenched disk is [80-1500]°C/min. The secondary γ' only nucleates at the beginning of the quench. This precipitation can be detected using dilatometric measurement at different cooling rates as shown in Fig.2. It appears that the start of precipitation is nearly independant of cooling rate : ±10°C for cooling rate varying in the current window. The amount of precipitates is independant of the cooling rate, as well.

The apparent heat capacity is the sum of absorbed or released energy of the material with the microstructure remaining constant, and of absorbed or released energy by the metallurgical transformations. This can be measured by on-cooling DTA (Fig.3).
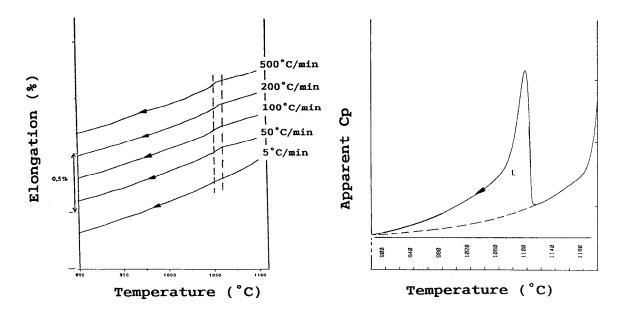
Fig.2:Dilatometric variation during the quench of Astroloy

Fig3.:Precipitation heat during quenching from above γ' -solvus

As the amount of precipitated γ' is constant and the precipitation kinetics are almost constant with cooling rate, we will consider that the effect of phase transformation on the energy balance and on the dilatometric change can be described as a function of temperature only. The effect of the strain and stress developed in a disk during quenching on the γ' precipitation kinetics will be neglected. This assumption will only be justified a posteriori by the correlation established between calculated and measured cooling rate and residual stresses.

MECHANICAL BEHAVIOUR IDENTIFICATION

The constitutive equation of Astroloy during the quench should possess the following properties :

-to take into account the switch from the high temperature behaviour to the low temperature behaviour,

-to describe independantly the temperature and the precipitation effect,

-to take into account isotropic and kinematic hardening for a correct description of successive tensile and compressive stresses.

The CHABOCHE-LEMAITRE behaviour was chosen [2] for which a monodimensionnal restriction is given in Fig.4. Its coefficients were identified by LMT using isothermal and kinematically complex fatigue loops performed on a MTS-machine [3]. The principle difficulty resulted from the necessity of keeping the γ' morphology constant during the whole testing. For this purpose, particular temperature cycles were chosen:

-1st step, solutionning the test specimen preforms and rapid quenching them to get a very fine γ' precipitation,

-2nd step, high temperature aging in order to coarsen the secondary γ' to the desired diameter,

-3rd step, rapid cooling to the testing temperature and achieving the whole deformation before γ' changes could occur. For the worst case the γ' diameter increased by 20% (Fig.5).

For the tests near the solutionning temperature, special care was taken not to change the primary γ' morphology and the γ grain size.

The identified plastic behaviour is compared to experimental stress measurements in Fig.6 :

-at high temperature (> 900°C); Astroloy exhibits a pure viscous flow stress,

-at low temperature, the classical "flat" stress/strain curve is observed,

-at intermediate temperature, both strain hardening and viscosity are observed.

Only a weak influence of γ' size was detected on the isotropic hardening and Young's modulus; thus leading to a new simplification of the mechanical model: the use of a microstructure related variable could be omitted.

The identified parameters were then smoothed with temperature as shown in Fig.7.
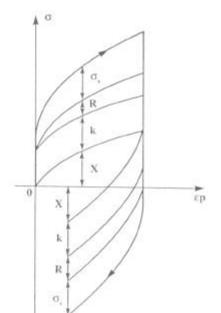
$$\dot{\epsilon} = \dot{\epsilon}_e + \dot{\epsilon}_p$$

$$\dot{\epsilon}_p = \frac{3}{2}\, \dot{p} \cdot \frac{S-X}{J2(S-X)}$$

$$\dot{p} = \frac{\langle J_2(S-X)-R-\sigma_Y \rangle^n}{K}$$

$$\text{with } J_2(S-X) = \sqrt{\frac{3}{2}(S-X):(S-X)}$$

$$\dot{R} = b(Q-R)\dot{p}$$
$$\dot{X} = \frac{3}{2}C\dot{\epsilon}_p - \gamma X \dot{p}$$

σv: viscous flow
R : isotropic hardening
k : true yield stress
X : Kinematic hardening

Fig.4: Monodimensionnal restriction of CHABOCHE-LEMAITRE constitutive equation.

precipitate size before deformation

structure preparation

mechanical deformation at constant structure

precipitate size after deformation
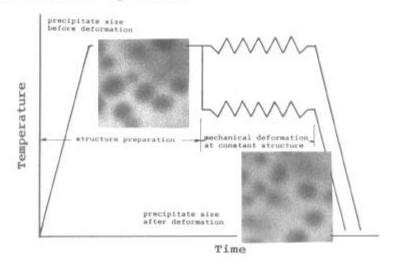
Temperature

Time

Fig.5: Temperature and microstructure evolution during the mechanical tests for identification of constitutive equation.
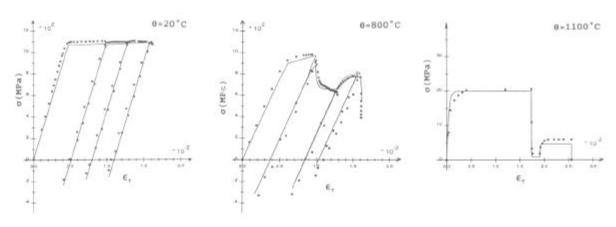
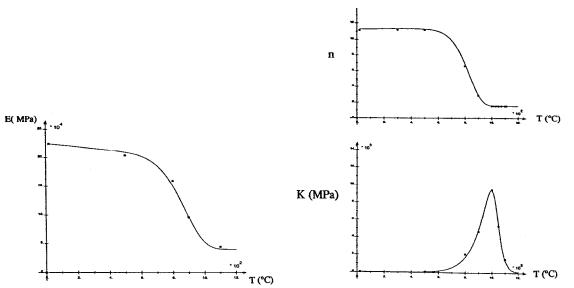

Fig.6: Measured and identified stress / strain curves.

Fig.7:   Evolution of some parameters of constitutive equation
          with temperature.

QUENCH MODELLING OF A TURBINE-DISK : THERMAL PREDICTION

An Astroloy HP-turbine-like disk was thermocoupled and quenched
at SNECMA's forge shop. The shape, dimensions and thermocouple
locations are displayed in Fig.8. The cooling curves had been
previously calculated using a Finite Difference software
developed by SNECMA, THBN. The heat transfer coefficients had
been identified using a IN718-disk quenched on the same
equipment. The basic method for this has already been described
in a previous Seven Springs conference by R.WALLIS [4]. The
experimental and predicted cooling curves are compared in
Fig.9. The precision obtained is typical of this method applied
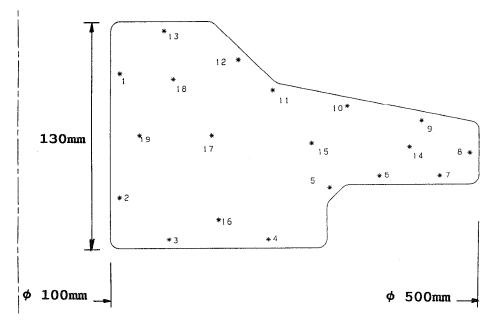to a wide range of disk shapes.

Fig.8:Shape of the oil-quenched disk and thermocouple locations
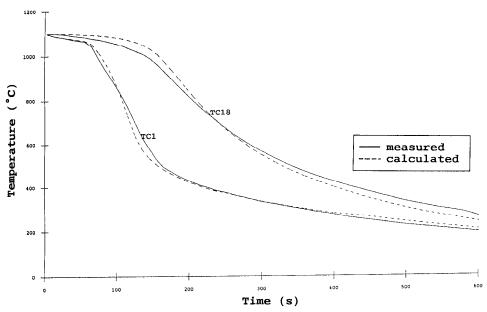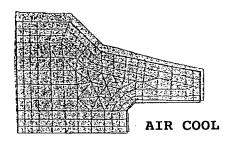
Fig.9:Comparaison between measured and predicted temperature

QUENCH MODELLING OF A TURBINE-DISK : MECHANICAL PREDICTION

The stress generation was calculated using the elasto-visco-plastic code called SAMCEF-VISCO [5]. The temperature loading was interpolated from results described above. The thermal expansion curve was taken using the data at 200°C/min. The constitutive equation was identified with a secondary γ' size at 170 nm.

Disc deformation

In order to understand how the deformation proceeds, two different cooling methods were analyzed: oil-quench and air-cooling. The deformed profiles are shown in Fig. 10. The general distortion appears more severe after oil-quench, as expected. In contrast, the evolution of the inner and outer diameter are opposite after both quenching methods. The examination of the intermediate stages reveals that during the rapid quenching the rim becomes elastic very early and imposes its displacement to the hot and still viscous massive section, whereas during the slow quenching the rim remains viscoplastic long enough to be deformed by the massive bore.
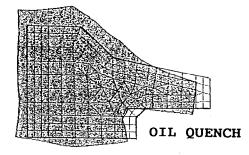

AIR COOL

OIL QUENCH

Fig.10:   Calculated contour after air cool and oil quench.
         (displacement magnification: 20X)

79

The profile of the quenched disc has been measured on 4
diameters at 45° and compared to the calculated section as
shown in Fig.11. The aspect of material displacement on both
cases is quite similar. A quantitative prediction of the inner
and the outer diameter variation allows a judgement of the
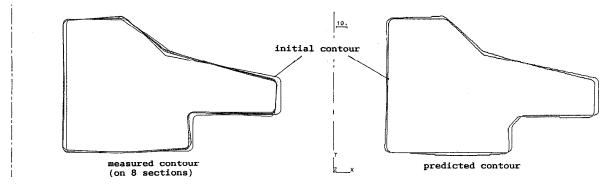precision of the model (table 1).

measured contour
(on 8 sections)

initial contour

predicted contour

Fig.11: Comparaison between measured and predicted contour
after oil quench.(displacement magnification: *5)

localization	calculation	measurement
bore	-0.43mm	-0.62mm
rim	-0.80mm	-0.80mm

Table 1: Calculated and measured inner and outer radius
displacement

Stress and strain history

The stress evolution within the disk depends classically on the
specific location. The surface, getting colder more rapidly,
would first sustain tensile stresses which become compressive
as the center of the disk gets colder. On the contrary, the
central part is first compressed then stressed in tension. This
is illustrated in Fig.12. The location of the highest
plasticity level (Fig.13) is the same as the hottest spot in
the disk. This shows that residual stresses are generated by
the viscous deformation of hot material stressed by cold
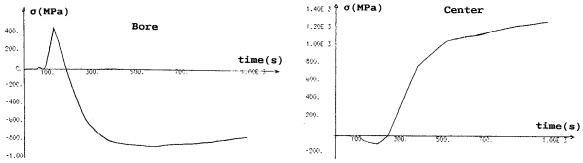elastic surroundings.

Fig.12: Evolution of calculated tangential stress component at
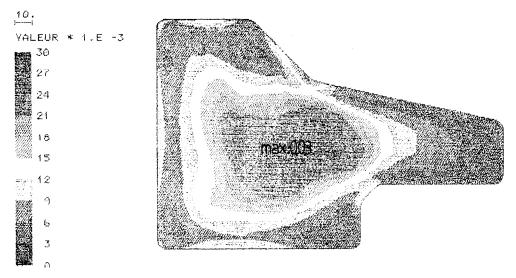the coldest and the hottest location of the disk
during quenching.
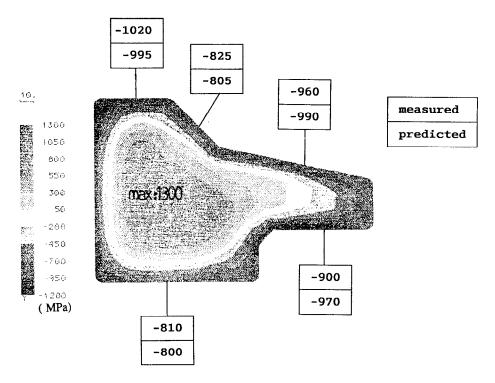
Fig.13:   Localisation of plastic deformation.

Fig.14:   Comparaison between measured and predicted tangential
          surface stress.

Residual stress level

In order to verify the high level of calculated residual
stresses (up to 1000 MPa), measurements were undertaken using
strain gauges stuck on the disk surface [6]. They were removed
by ECM machining a 4-mm thick plate around them. The opposite
of the deformation measured after machining multiplied by
Young's modulus is the stress resulting from the quench. The
strain gauges were oriented in order to measure the tangential

81

and the radial surface components. A correlation between the measured and the calculated tangential stresses is given in Fig.14. and shows an aggreement within 10%.
Nevertheless, it has to be noted that due to the plasticity the surface stress information is not sufficient to derive the internal stress using the mechanical equilibrium equation. This further result is being processed by analyzing the disk deformation during machining.

CONCLUSIONS

-A model for the prediction of residual stresses in quenched superalloy disk has been presented. The method for identifying the material behaviour was one key issue of this development; it has been applied to Astroloy. This method could also be used for other superalloys, such as N18 and DA718, if transformation plasticity is negligible compared to viscoplastic flow.

-The calculated stress level reached during the quench may be very high. The measurements of displacement and surface residual stresses performed on a real disk support the model results. Further experiments are to be made to confirm the internal stress level.

-Prediction of the residual stresses in the finished disk needs further developments, basically to answer the following questions: -what is the thermal relaxation during aging, -what is the mechanical relaxation during machining.

REFERENCES
[1]   S.DENIS, E.GAUTIER, A.SIMON and G.BECK, "Stress phase transformation interactions-Basic principles,modelling and calculation of internal stresses", Mat.Sci.and Tech., (Oct.1985),805-814
[2]   J.LEMAITRE, J.L.CHABOCHE, "Mécanique des matériaux solides", (PARIS:Dunod,1985)
[3]   F.DEVY, "Description, modélisation et simulation de la trempe des superalliages", (thèse de l' université, PARIS_VI,1991)
[4]   R.A.WALLIS and P.R.BHOWAL, "Properties optimization in superalloys through the use of heat treat modelling", SUPERALLOYS 88, D.N.DUHL and al., (Warrendale,PA:The Metallurgical Society,1988), 525-534
[5]   J.C.GOLINVAL, "Calcul de structures soumises à des chargements cycliques à hautes températures", (thèse de docteur-ingénieur, univ.Liège,1989)
[6]   B.GEORGE, "Mesures de contraintes internes dues au traitement thermique dans un disque de turbine en Astroloy", (Rapport Hispano-Suiza, Bois-Colombes, 1992)