# Hot Isostatic Pressing of SY625 Powder

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Abstract

Hot Isostatic Pressing (HIP) is an established process for compacting powder materials far below their melting point. It allows to produce net-shape parts in order to reduce machining costs or to obtain non machinable geometries. In the HIP process, a steel container is filled with the superalloy powder, out-gassed, and then submitted to simultaneous application of high pressure (about 100MPa) and a temperature of about 1150°C for several hours. Porosity is then completely eliminated.

To produce net-shape parts, it is essential to be able to forecast the behaviour of the powder and steel container during the HIP process in order to predict the final geometry of the product. Numerical simulation can provide much information about the final as well as intermediate stages of the HIP process.

The use of simulation requires the constitution of materials data files containing physical and thermo-mechanical properties of the materials, including coefficients of the porous constitutive equations for powder. In this work, the SY625 data not available in the literature have been determined experimentally. Uniaxial compression tests have been used to determine creep law parameters for dense and porous materials. Data base for steel container is also available for a large range of temperature.

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## Introduction

Hot Isostatic Pressing (HIP) is an established process for compacting powder materials far below their melting point. Processing of superalloy powders using HIP has been used for many years in different industrial applications, especially to produce high quality parts with complex geometry. In the HIP process, a steel container is filled with superalloy powder, out gassed and then submitted to simultaneous application of high pressure (about 100 MPa) and a temperature of about 1150 °C for several hours. During the process, porosity is completely eliminated, so volume is reduced of about 30 %. It is important to obtain net-shape HIP parts in order to reduce machining costs or even to produce non-machineable geometries. However, the final geometry of the product can not be simply deduced from the initial one, due to container stiffness and temperature gradients during consolidation process. To produce net-shape parts, it is essential to be able to forecast the behaviour of the superalloy powder and steel container during HIP process in order to predict the final geometry of the product. Numerical simulation can provide much information about the final as well as intermediate stages of the HIP process.

A special tool has been developped by CEA/CEREM in the frame of the ISOPREC® project for the design and modelling of container used to produce net-shape parts using Hot Isostatic Pressing (HIP). This tool is constituted of three modules : PreCAD®/D for the design of the parts and meshing, PreCAD®/M for the modelling of consolidation of the powder, and PreCAD®/B for the data base of materials including powders and container. A detailed description of this tool is given in a previous paper [1]. We will only detail here the constitution of the material data file and especially the determination of parameters of the constitutive law used for the simulation.

The superalloy considered in this study is the SY625, a solid solution-strenghtened nickel base superalloy produced by TECPHY, France. Its composition is given in table I.

Table I: Chemical analysis of the SY625 (in % weight)

| | | | |
|---|---|---|---|
| **Ni** | Bal. | **Co** | 0.014 |
| **Cr** | 20.4 | **Fe** | 0.2 |
| **Mo** | 8.6 | **Si** | 0.18 |
| **Nb** | 3.4 | **Ti** | 0.01 |
| **C** | 0.013 | | |

## Description of the theoretical model

Inorder to simulate consolidation of powder, a macromechanical approach is used. Powder is considered as a continuous medium with relative density as an internal variable. The relative density $\rho$ is defined as the ratio of the apparent density to the density of the fully dense material. The behaviour of the powder during consolidation is modelled by constitutive equations based on continuous media mechanics for viscoplastic metals. The flow formulation for compressible viscoplastic materials proposed by Abouaf [2] is used. This model extends, for hot deformation, the Green's approach [3] for cold deformation.

Constitutive equations for porous materials are developed in the framework of continuous mechanics. It is an extension of the classical $J_2$ Mises theory allowing volume changes during viscoplastic flow. The equivalent stress $\sigma_{eq}$, which includes the effect of pressure, is defined as:

$$\sigma_{eq} = \sqrt{fS_1^2 + \tfrac{3}{2}c\bar{S}_2^2}$$

with

| | |
|---|---|
| $S_1 = \mathrm{Tr}(\tilde{\sigma})$ | first invariant of the stress tensor |
| $\bar{S}_2^2 = \mathrm{Tr}(\tilde{\bar{\sigma}}.\tilde{\bar{\sigma}})$ | second invariant of the stress tensor |
| $\tilde{\bar{\sigma}} = \tilde{\sigma} - \frac{1}{3}S_1\tilde{\delta}$ | deviator of the stress tensor |

where $\tilde{\sigma}$ is the Cauchy stress tensor and $\tilde{\delta}$ is the unity second order tensor. c and f are two functions representing the stress localisation induced by porosity, and which a priori depend only on the relative density $\rho$. For full density ($\rho$=1), c=1 and f=0 so that the equivalent stress defined for the porous metal is equivalent to the classical Mises equivalent stress.

## Identification of the parameters

In order to identify those two parameters we made experiments inwhich the thermomechanical path is simple enough to allow us to have an analytical expression for f and c.

- During a Hot Isostatic Pressing of a cylinder where the compact doesn't reach the full density, we have

$$f = \frac{1}{9}\left(\frac{\dot{\rho}/\rho}{AP^n}\right)^{2/n+1}$$

$\rho(t)$ is the evolution of the relative density with the step duration ( pressure and temperature being constant) of the HIP cycle, $\dot{\rho}$ is its derivation. P is the applied pressure.

A and n are the parameters of a Norton creep law for the dense material. They are independent from the density and are identified on the dense material using uniaxial compression tests at different temperatures and strain rates.

- During a high temperature compression of porous samples, we can reach

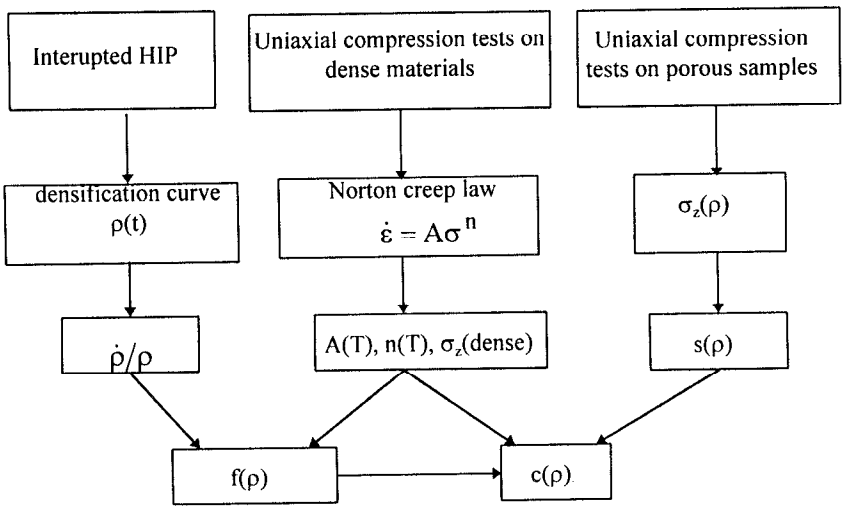



Figure.1: General framework of the experimental determination

with $c = s^{-2n/n+1} - f$

$$s = \frac{\sigma_z(\rho)}{\sigma_z(\text{dense})}$$

where s is the ratio of the yield stress of porous sample on the yield stress of the dense one.
The experimental function s(ρ) is first determined, then the rheological function c is calculated.

This identification method is summarized in figure 1.

Interupted HIP

f is density dependent, we must therefore choose T and P in order to have a densification curve with a large range of density. Because of the high temperature and pressure of the industrial cycle (1150°C and 100 MPa), the compact at the end of the raising is close to be dense, thus we choose 950°C, 20 MPa and 950°C, 60 MPa. (figure 2). Those two cycles have the same duration of the simultaneous temperature and pressure raising, 54 min. For each HIP cycle, different step durations have been performed. The relative density is then ranging from 78% to 97% of the dense material, the tap density being 73%; this high value is the consequence of the large dispersion of the powder's granulometry. A simple time derivation of the interpolated curves, ρ(t) is then performed to obtain the master curves relating the densification rate to the relative density. From those curves and knowing the creep parameters, it is possible to establish the curve f(ρ).

Creep law parameters

The simulation requires the knowledge of the creep law for all the involved materials: the SY625 powder and the mild steel the container is composed of. We performed uniaxial compression tests at all the temperatures (from 900°C to 1150°C) and strain rates (from $4.10^{-6}$ $s^{-1}$ to $10^{-3}$ $s^{-1}$) that the materials are liable to undergo.

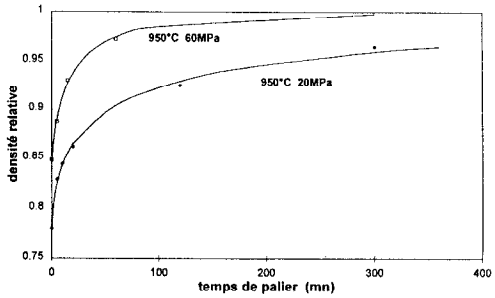


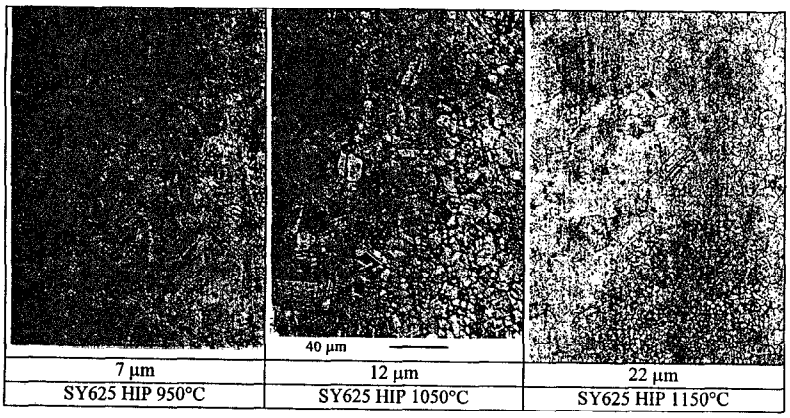

Figure. 2: Densification curves of SY625 at 950°C 20MPa and 60MPa.

The experiments were conducted with a 10t press fit out with a high temperature halogen lamp furnace, at constant cross bar speed with the strain rate jump method.
The dense samples of nickel based superalloy SY625 were hipped at 950°C, 1000°C, 1050°C and 1150°C and the compression tests were made between 950°C and 1100°C. The results are given in table II

They show a great difference from bibliographic data especially [4] where n decrease from 6 to 4 between 900°C and 1150°C. The coefficient of stress sensivity, n, seems to be almost constant around 2.2, if the test temperature is equal to the HIP temperature, whereas it undergoes a great jump if the test temperature is lower than the HIP temperature. We compare those values with the grain coarsening during HIP (fig. 3). It seems that the two values are related.
The n value is thus the result of two competing phenomenons: on one hand, n may decrease with increasing temperature, but on the other hand, it may increase with increasing grain size [5].
All we can conclude now is that the temperature of fabrication, and then the grain size, has a strong influence on the creep properties of the P/M SY625 alloy.

Table II: Creep law parameters of the P/M SY625

| Test T °C | 950 | | | 1000 | 1050 | 1100 |
|---|---|---|---|---|---|---|
| HIP T °C | *950* | *950* | *1150* | *1000* | *1050* | *1150* |
| n | 2.4 | 2.2 | 3.8 | 2.3 | 2 | 2.1 |




| 7 µm | 12 µm | 22 µm |
|---|---|---|
| SY625 HIP 950°C | SY625 HIP 1050°C | SY625 HIP 1150°C |

figure. 3: photomicrographs of P/M SY625 after HIP at 100MPa and 950°C, 1050°C, 1150°C and the corresponding mean grain size.

We have chosen to determine the creep law at the same temperature the samples have been hipped in order to have in the data base the A and n values of the material in a state as close as possible as it is during the heating up.

Uniaxial compression tests on porous samples

The porous samples obtained from interupted HIP cycles underwent uniaxial compression tests at 950°C at a strain rate of $10^{-4}$ $s^{-1}$. The s function is then plotted for density ranging from 78% to 100% of the relative density. We made in addition one test on a sample hipped at 1050°C 20 MPa (ρ=88%)

The rheological functions f and c

The densification curves and the knowledge of the creep law allow to identify f on a large scale of density (figure 4). The c function follows the compression tests on porous samples (figure 5).
The sample hipped at 1050°C 20 MPa, the two densification curves (20 MPa and 60 MPa) and the few difference it leads in the rheological functions justify the Abouaf's hypothesis: f and c are not dependent on the pressure and temperature; what confirms results of previous studies made on TA6V [6] and 316LN [7].

Conclusions

The data base needed to simulate the consolidation of P/M SY625 consists of two rheological parameters (f and c) and some physical properties such as Young modulus, Poisson's ratio, thermal expansion coefficient, creep properties, thermal conductivity, ... .
The f and c coefficients have been experimentally determined. This study justifies one of the main hypothesis of the Abouaf's law: f and c are independent of temperature and pressure.
The other parameters are known from a bibliographic study.
The next step is now to use PreCAD® to simulate HIP consolidation of SY625 powder to manufacture net shape parts using ISOPREC®.

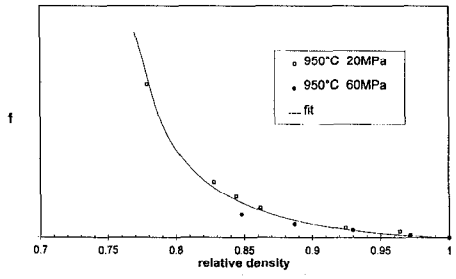



Figure. 4: Shape of the f function of P/M SY625

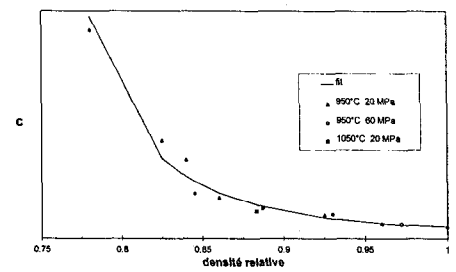



Figure 5: Shape of the c function of P/M SY625