"HIP Modeling Methodology Based on the Inherent Process Anisotropy

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Abstract

The "net shape" HIP approach is based on computer programs with embedded engineering models of powder consolidation, shrinkage and surface formation that use the computer aided design (CAD) of the part needed and of the HIP tooling. Densification pattern during HIP, which is the "key" to "net shape" technology is determined by the capsule and powder materials rheology and is, at the initial stages, controlled by the capsule's plastic stiffness.

However, dilatometric experiments on HIP of capsules with powder revealed that even at the final stages of densification when the capsule is pliable, deformations are not uniform and follow the dominating radial or axial component though the pressure is isostatic and of uniform density. Deformation pattern is determined by a form of deformation history, such that some "anisotropy" generated during this history becomes inherent and this, in turn, controls the process of shrinkage even under uniform pressure of HIP.

Following this approach, the equations describing the material model during HIP have been modified and appropriate experiments carried out for their parametrical identification.

Anisotropic behavior of powder material during "net shape" HIP consolidation, discovered during special experiments with porous samples, was demonstrated experimentally and by introducing an anisotropy module within the entire HIP process numerical model.

Basic Hypotheses and Equations

The advancement towards "net shape" HIP is provided by the process modeling and HIP tooling design . The proposed steps to highly desirable "net shape" products are improvements to existing process models used to design HIP tooling. The more advanced modeling must fully account for the evolution of material properties during HIP cycles. In other words, the powder rheology may depend on the inherent anisotropy caused by the evolution of pores during consolidation.

These mechanisms provide additional control of capsule/powder shrinkage during HIP.

To introduce inherent anisotropy caused in HIP triggered by initial difference in capsule stiffness and then developed due to the pore evolution, it is necessary to accept the following basic hypotheses.

1. **Hypothesis N1.**

There exists a plastic potential , i.e., there exists a yield surface, $f(\sigma_{ij}, \mu_k) = 0$, where $\varepsilon_{ij} = \lambda \frac{\partial f}{\partial \sigma_{ij}}$ and μ_k -are some kinetic parameters.

2. **Hypothesis N2.**

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Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **APR 2005**	2. REPORT TYPE	3. DATES COVERED **-**
4. TITLE AND SUBTITLE **HIP Modeling Methodology Based on the Inherent Process Anisotrophy**		5a. CONTRACT NUMBER
		5b. GRANT NUMBER
		5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S) **Victor Samarov; Vassily Goloveshkin; Charles Barre**		5d. PROJECT NUMBER **OSDB**
		5e. TASK NUMBER **R4PT**
		5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Synertech P/M, Inc.,11652 Monarch St.,Garden Grove,CA,92841-1817**		8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR’S ACRONYM(S)
		11. SPONSOR/MONITOR’S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT
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15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**		**8**	

The shape (the equation) of the yield surface depends only on the current values of accumulated deformations, not on the process history (trajectory). It means that the surface equation is as follows: $f(\sigma_{ij}, \varepsilon_{ij}) = 0$.

3. Hypothesis N3.

The initial state of the powder material is isotropic. It means that in the principal system axes of deformation tensor the following equation is valid: $f = f(\sigma_{ij}, \varepsilon_1, \varepsilon_2,, \varepsilon_3) = 0$.

We also presume that the equation for the surface can be presented as a quadratic form.

Assuming all of this, the equation for the yield surface can be presented as:

$$f = g_1\sigma_1^2 + g_2\sigma_2^2 + g_3\sigma_3^2 + g_{12}\sigma_1\sigma_2 + g_{13}\sigma_1\sigma_3 + g_{23}\sigma_2\sigma_3 +$$
$$d_{12}\sigma_{12}^2 + d_{13}\sigma_{13}^2 + d_{23}\sigma_{23}^2$$

where the functions g, d are the functions of $\varepsilon_1, \varepsilon_2, \varepsilon_3$.

Let us consider an experiment on axisymmetric upsetting of a cylindrical specimen with the density ρ along the axis "3".

Then $\varepsilon_1 = \varepsilon_2 = \tilde{\varepsilon}$, $\varepsilon_3 = \varepsilon$, $2\tilde{\varepsilon} + \varepsilon = 3e_1$

Then the yield surface equation can be presented as follows:

$$g(\tilde{\varepsilon},\rho)\sigma_1{}^2 + g(\tilde{\varepsilon},\rho)\sigma_2{}^2 + g(\varepsilon,\rho)\sigma_3{}^2 + 2\psi(\varepsilon,\rho)\sigma_1\sigma_2 + 2\psi(\tilde{\varepsilon},\rho)\sigma_1\sigma_3 +$$
$$+2\psi(\tilde{\varepsilon},\rho)\sigma_2\sigma_3 + 2d(\varepsilon,\rho)\sigma_{12}{}^2 + 2d(\tilde{\varepsilon},\rho)\sigma_{13}{}^2 + 2d(\tilde{\varepsilon},\rho)\sigma_{23}{}^2 = \sigma_s{}^2$$

Then, if we consider upsetting a specimen cut-off at the angle φ to the axis (1) in the plane perpendicular to the axis (3) the results should not depend on the value of φ.

Let us designate upsetting stress as σ.

Then: $\sigma_3 = 0$,

$\sigma_{31} = \sigma_{32} = 0$,

$\sigma_1 = \sigma \cos^2 \varphi$,

$\sigma_2 = \sigma \sin^2 \varphi$,

$\sigma_{12} = \sigma \cos\varphi \sin\varphi$.

If we substitute these values in the equation for the yield surface, we shall obtain the following:

$$\sigma^2\left[g(\tilde{\varepsilon},\rho)(\cos^4\varphi + \sin^4\varphi) + 2\psi(\varepsilon,\rho)\sin^2\varphi\cos^2\varphi + 2d(\varepsilon,\rho)\sin^2\varphi\cos^2\varphi\right] = \sigma_s{}^2$$

or

$$\sigma^2\left[g(\tilde{\varepsilon},\rho) + 2\sin^2\varphi\cos^2\varphi(\psi(\varepsilon,\rho) + d(\varepsilon,\rho) - g(\tilde{\varepsilon},\rho))\right] = \sigma_s{}^2$$

Due to the axial symmetry, the value of σ does not depend on φ.

Then: $d(\varepsilon,\rho) = g(\tilde{\varepsilon},\rho) - \psi(\varepsilon,\rho)$

Where $2\tilde{\varepsilon} + \varepsilon = 3e_1 = \sqrt[3]{\dfrac{\rho_0}{\rho}} - 1$

Plan of Experiments

The following experiments were carried out to determine and characterize the functions. There will be two types of experiments: experiments with the "isotropic" material (#1 and #2) and experiments with "non-isotropic" material (#3, #4 and #5).

1. **Experiment #1**.

HIP in a thin-walled symmetrical capsule with the deformation tensor being close to the spherical one. Then,

$$\varepsilon_1 = \varepsilon_2 = \varepsilon_3 = \sqrt[3]{\frac{\rho_0}{\rho}} - 1 = e_1$$

As $\sigma_1 = \sigma_2 = \sigma_3 = P(\rho)$, the plasticity criterion will give the following relation for the two functions:

$$g(e_1,\rho) + 2\psi(e_1,\rho) = \frac{\sigma_s^2}{3P^2}$$

2. **Experiment #2.**

Uniaxial deformation (upsetting) of the samples obtained in Experiment #1. Then, $\sigma_1 \neq 0, \sigma_2 = \sigma_3 = 0$ and as a result, we get the second relation:

$$g(e_1,\rho) = \frac{\sigma_s^2}{\sigma_1^2}$$

and can, therefore, determine the values for both functions in the point (ρ, e_1).

The value for the third function in this point (ρ, e_1) can be derived if we consider upsetting of this isotropic material along the axis other than "1" which leads to the following relation:

$$d(e_1,\rho) = g(e_1,\rho) - \psi(e_1,\rho)$$

3. **Experiment #3.**

HIP in a thick walled capsule leading to practically uni-directional deformation along the axis "1". For this deformation model

$$\varepsilon_2 = \varepsilon_3 = 0, \varepsilon_1 = e_2 = \frac{\rho_0}{\rho} - 1$$

Letting the axial stress be $\sigma_я$, and using the equation for the yield surface and the condition that both of the deformations in the directions orthogonal to "1" are equal to zero, we can get the following relation

for the functions: $g = g(\varepsilon,\rho)$, $\psi = \psi(\varepsilon,\rho)$ in the two points: $\varepsilon = 0, \varepsilon = e_2 = \frac{\rho_0}{\rho} - 1$

$$g(e_2,\rho) - \frac{2\psi^2(0,\rho)}{g(0,\rho) + \psi(e_2,\rho)} = \frac{\sigma_s^2}{\sigma_z^2}$$

4. **Experiment #4.**

Uniaxial deformation (upsetting) of the samples obtained in Experiment #3 in the direction of the maximal deformation.

If the flow stress of upsetting is s_1, then the equation for the yield surface will provide the second relation, enabling us to determine $g = g(e_2, \rho)$:

$$g(e_2, \rho) = \frac{\sigma_s^2}{s_1^2}$$

The ratio between the deformations in the direction "1" and orthogonal direction (an analogue of the Poisson coefficient) $\beta_1 = \frac{\varepsilon_{22}}{\varepsilon_{11}}$ will give the third relation between the functions:

$$\beta_1 = \frac{\psi(0, \rho)}{g(e_2, \rho)}$$

5. Experiment #5.

Uniaxial deformation (upsetting) of the samples obtained in Experiment #3 in the direction orthogonal to the maximal deformation.

If the flow stress of upsetting is s_2, it will give the fourth relation for the functions:

$$g(0, \rho) = \frac{\sigma_s^2}{s_2^2}$$

As a result, we can obtain the values of two functions in two more points in addition to the values determined after Experiments #1 and #2.

For the third function, due to isotropic properties in the directions orthogonal to the maximal deformation, we get the relations in the points

$$d = d(e_2, \rho)$$

and

$$d(e_2, \rho) = g(0, \rho) - \psi(e_2, \rho)$$

As a result of the treatment of experimental data, we get the values of the first two functions in three points ($\varepsilon = 0$, $\varepsilon = e_1$, $\varepsilon = e_2$), and for the third function, in two points ($\varepsilon = e_1$, $\varepsilon = e_2$), for a given value of density reached during HIP, i.e., to reveal the effect of deformation "anisotropy".

Carrying out experiments for several HIPed densities, it becomes possible to build approximations for these three functions $g = g(\varepsilon, \rho)$, $\psi = \psi(\varepsilon, \rho)$, $d = d(\varepsilon, \rho)$.

For the isotropic HIP model, the functions of the plasticity criterion depend on density only.

Actually "anisotropy" introduced in the proposed model is based on the assumption of the existence of the "areal density" and is determined by the values of density and of the normal deformation in the principal axes.

Development of the Database for Rheological Coefficients of the Anisotropic Model

Five special sets of experiments with isostatic and anisotropic loading were envisaged to the values of the functions $g = g(\varepsilon,\rho)$, $\psi = \psi(\varepsilon,\rho)$, $d = d(\varepsilon,\rho)$ and of the influence coefficient β for several HIPed densities.

Titanium powder alloy Ti-6Al-4V was chosen as a candidate to gain experience on producing complex shaped components. Keep in mind that Ti-6Al-4V only showed most of the distortions and hard-to-predict features for the titanium alloy rather than for Ni-base alloys.

To provide uni-axial deformation during HIP and create initial anisotropy of the deformation pattern, special thick walled capsules with the increased radial stiffness from mild 1018 steel were designed and manufactured to carry out parametric identification.

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HIP in a thin-walled symmetrical capsule with the deformation tensor being close to the spherical one.

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As $\sigma_1 = \sigma_2 = \sigma_3 = P(\rho)$, the plasticity criterion will give the following relation for the two functions:

$$g(e_1,\rho) + 2\psi(e_1,\rho) = \frac{\sigma_s^2}{3P^2}$$

2. Experiment #2.

Uniaxial deformation (upsetting) of the samples obtained in Experiment #1. Then, $\sigma_1 \neq 0, \sigma_2 = \sigma_3 = 0$ and as a result, we get the second relation:

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The value for the third function in this point (ρ, e_1) can be derived if we consider upsetting of this isotropic material along the axis other than "1", which leads to the following relation: $d(e_1,\rho) = g(e_1,\rho) - \psi(e_1,\rho)$.

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HIP in a thick-walled capsule leading to practically uni-directional deformation along the axis "1".

For this deformation mode

$$\varepsilon_2 = \varepsilon_3 = 0, \varepsilon_1 = e_2 = \frac{\rho_0}{\rho} - 1$$

Let the axial stress be $\sigma_я$, then, using the equation for the yield surface and the condition that both of the deformations in the directions orthogonal to "1" are equal to zero, we can get the following relation for the functions: $g = g(\varepsilon,\rho)$, $\psi = \psi(\varepsilon,\rho)$ in the two points:

$$\varepsilon = 0, \varepsilon = e_2 = \frac{\rho_0}{\rho} - 1$$

$$g(e_2,\rho) - \frac{2\psi^2(0,\rho)}{g(0,\rho)+\psi(e_2,\rho)} = \frac{\sigma_s^2}{\sigma_z^2}$$

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Uniaxial deformation (upsetting) of the samples obtained in Experiment #3 in the direction of the maximal deformation.

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The ratio between the deformations in the direction "1" and orthogonal direction (an analogue of the Poisson coefficient) $\beta_1 = \frac{\varepsilon_{22}}{\varepsilon_{11}}$ will give the third relation between the functions:

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If the flow stress of upsetting is s_2, it will give the fourth relation for the functions:

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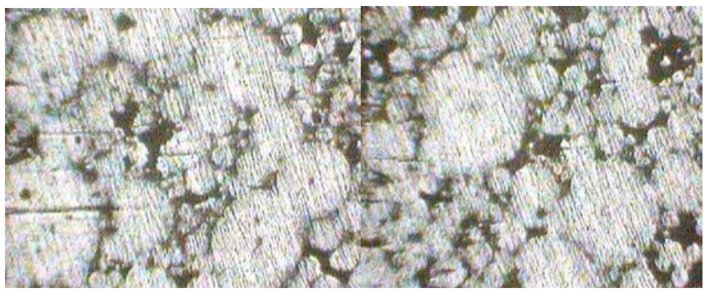
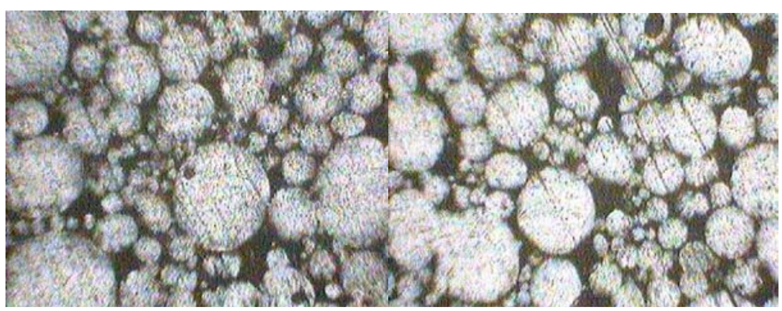
Figures 1 and 2 present the results of micro-structural analysis of the mounts taken from the samples oriented in different orthogonal directions. These photos definitely reveal the existence of the “areal density” phenomenon, when the deformation and density pattern provides initial anisotropy.

The results of the compression tests were processed in order to be incorporated into the HIP model and to update the anisotropy module with actual data received from the experiments.



x100 x100

Figure 1. Typical Micro-structures of a Porous Sample in the Direction Orthogonal to Main Deformation Axis (Average Density 80%)



x100 x100

Figure 2. Typical Micro-structures of a Porous Sample in the Direction of the Main Deformation Axis (Average Density 81%)

CONCLUSIONS

Anisotropic behavior of Ti-6Al-4V atomized spherical powder during HIP

Consolidation, caused by the initial non-uniform capsule stiffness, was revealed during special experiments. The values of the flow stress s_1 of the samples cut off in the direction of the maximal deformation, processed in Experiment #4, are about 30% higher than the flow stress s_2 of the samples cut off in the direction orthogonal to the maximal deformation processed in Experiment #5.

Potential for "net shape" HIP technology based on advanced process modeling accounting inherent process anisotropy, to reduce cost and/or time required to produce specific liquid rocket engine components was analyzed.

This development effort has provided a general proof of viability of proposed "net shape" HIP technology based on the advanced process modeling.

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