international journal of

powder metallurgy

September/October 2008

Focus Issue:
Hot Isostatic Pressing

44/5

HIPing: More than a Niche Technology
HIPing Equipment Technology
Large-Scale HIPed Components
HIP Clad Wear-Resistant Briquetting Tools
HIPing Simulation for Titanium

Publisher
C. James Trombino, CAE
jtrombino@mpif.org

Editor-in-Chief
Alan Lawley, FAPMI
alan.lawley@drexel.edu

Managing Editor
James P. Adams
jadams@mpif.org

Contributing Editor
Peter K. Johnson
pjohnson@mpif.org

Advertising Manager
Jessica S. Tamasi
jtamasi@mpif.org

Copy Editor
Donni Magid
dmagid@mpif.org

Production Assistant
Dora Schember
dschember@mpif.org

President of APMI International
Nicholas T. Mares
ntmares@asbury.com

Executive Director/CEO, APMI International
C. James Trombino, CAE
jtrombino@mpif.org

international journal of powder metallurgy

Contents 44/5 September/October 2008

FOCUS: Hot Isostatic Pressing

DEPARTMENTS

Cover: Welding of HIPing container. *Photo courtesy Crucible Materials Corporation, Pittsburgh, Pennsylvania.*

The *International Journal of Powder Metallurgy* (ISSN No. 0888-7462) is a professional publication serving the scientific and technological needs and interests of the powder metallurgist and the metal powder producing and consuming industries. Advertising carried in the *Journal* is selected so as to meet these needs and interests. Unrelated advertising cannot be accepted.

Published bimonthly by APMI International, 105 College Road East, Princeton, N.J. 08540-6692 USA. Telephone (609) 452-7700. Periodical postage paid at Princeton, New Jersey, and at additional mailing offices. Copyright © 2008 by APMI International. Subscription rates to non-members; USA, Canada and Mexico: $95.00 individuals, $220.00 institutions; overseas: additional $40.00 postage; single issues $50.00. Printed in USA by Cadmus Communications Corporation, P.O. Box 27367, Richmond, Virginia 23261-7367. Postmaster send address changes to the *International Journal of Powder Metallurgy*, 105 College Road East, Princeton, New Jersey 08540 USA USPS#267-120

ADVERTISING INFORMATION
Jessica Tamasi, APMI International
105 College Road East, Princeton, New Jersey 08540-6692 USA
Tel: (609) 452-7700 • Fax: (609) 987-8523 • E-mail: jtamasi@mpif.org

APMI INTERNATIONAL

HOT ISOSTATIC PRESSING SIMULATION FOR TITANIUM ALLOYS

Takuji Teraoku*

In aerospace, gas turbines, and other critical areas, titanium-base alloys are used due to their low weight and high strength. These alloys have a high melting point and are difficult to machine. In consequence, hot isostatic pressing (HIPing) of titanium alloy powder is a preferred method for processing. The cost of HIPed parts can be reduced by minimizing material waste and by reducing machining. To utilize near-net-shape powder metallurgy (PM) processing, it is important to determine the initial capsule dimensions. Methods for predicting the final dimensions of the HIPed product by simulation using numerical-solution techniques exist. Current computer technology enables finite element (FE) simulation for the HIPing of metal powders. In this study, we describe methods for calculating material properties, cite the input data required for simulation, and compare our simulation values with results obtained from actual Ti-6Al-4V products.

NUMERICAL SIMULATION AND ANALYSIS

MSC.Marc, a non-linear FE program[1] was used for numerical simulation and analysis. A unified viscoplastic approach was selected from this program for simulating the HIPing of metal powder. This simulation is a thermomechanically coupled analysis since both mechanical properties and thermal properties are prescribed. Furthermore, the material behavior is both temperature and density dependent. The powder is represented by means of a modified Shima model.[2]

The yield function is:

$$F = \frac{1}{\gamma}\left(\frac{3}{2}\,\sigma^d\sigma^d + \frac{p^2}{\beta^2}\right)^{1/2} - \sigma_y \qquad (1)$$

where σ_y is the uniaxial yield stress, σ^d is the deviatoric stress tensor, where $\sigma^d\ \sigma^d$ specifies $\sigma^d_{ij}\ \sigma^d_{it}$ and p is the hydrostatic pressure. γ and β are material parameters. σ_y can be a function of temperature and relative density and γ and β are functions of relative density only. For β and γ:

$$\beta = (q_1 + q_2\rho^{q_3})^{q_4} \qquad (2)$$

$$\gamma = (b_1 + b_2\rho^{b_3})^{b_4} \qquad (3)$$

where ρ is the relative density and q_1, q_2, q_3, q_4, b_1, b_2, b_3, b_4, are parameters derviced from compression tests for the determination of γ and β.

As the powder mass densifies, ρ approaches 1 and the classical von Mises model is operative.

DETERMINATION OF MECHANICAL PROPERTIES

A uniaxial compression test was performed to determine the parameters γ and β in the Shima model. Details of the test method have been described by Yabu et al.[3]

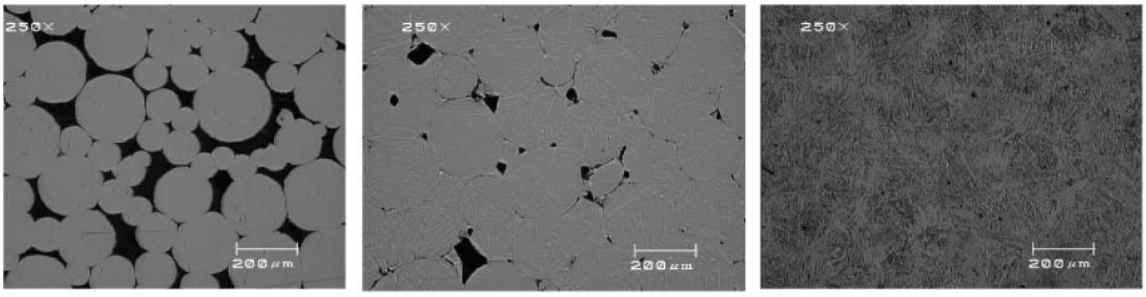
Fabrication of Test Specimens

HIPing conditions were determined to obtain test specimens of different relative densities. HIPed test specimens were machined into cylinders prior to the measurement of relative density. The relative densities of the HIPed specimens were 82.8%, 90.3%, and 100%, respectively, of the pore-free values. Figure 1 shows scanning electron

Presented at HIP '08, the 9th International Conference on Hot Isostatic Pressing, organized by IHC, the International HIP Committee, May 2008, Huntington Beach, California

---

**Manager, Technical Center, Kinzoku Giken Co. Ltd., Tokyo, Japan; E-mail: t_teraoku@kinzoku.co.jp*



$\rho = 82.8\%$ $\rho = 90.3\%$ $\rho = 100\%$

Figure 1. *Microstructure at end surface of test specimens. SEM/BSI*

micrographs (SEM) in the backscattered electron image mode (BSI) of the microstructure at the ends of the test specimens for the three relative density levels.

Uniaxial Compression Test

Uniaxial compression tests were performed at ambient temperature, 700°C, and 900°C and at strain rates of 1.4E-3/s, 1.4E-4/s, and 1.4E-5/s. The tests were performed in vacuum on a high-temperature tension/compression test machine with a maximum temperature capability of 1,100°C and maximum load capacity of 100kN, Figure 2.

Calculation of β and γ

The uniaxial compression test gives the values of $\sigma_{11} = \rho$, $\sigma_{22} = \sigma_{33}$, $\sigma_{ij} = 0$ $(i \neq j)$. By measuring the incremental strain during a specified period of compression, β can be obtained from the relation:

$$\beta = \left\{ (2/3) \frac{d\varepsilon_{11}{}^{P} - d\varepsilon_{22}{}^{P}}{dePij} \right\}^{-0.5} \qquad (4)$$

Figure 2. *High-temperature tension/compression test machine*

The parameter γ can be found by plotting the yield point ratio $\sigma_o{}^{*}/\sigma_o$ as a function of relative density ρ, where $\rho_o{}^{*}$ is the yield strength at each density level and σ_o is the yield strength at the pore-free density.

Other Data

It is necessary to take into account the mechanical properties and heat transfer properties of the powder that are dependent on temperature and relative density. To this end, the values of Young's modulus, Poisson's ratio, yield point, heat-transfer ratio, and specific heat were used as a function of temperature and relative density. For the capsule, its mechanical properties and heat-transfer properties were used which were functions of temperature.

MANUFACTURE OF HIPED PM TI-6AL-4V COMPOSITE

Ti-6Al-4V Powder

The powder used in this study was manufactured by the plasma rotating electrode process (PREP).

Turbine Disk

After fabricating the capsule from jointed cold-reduced carbon sheet steel (SPCC, JIS G 3141), it was filled with powder and HIPed. Figure 3 shows the capsule before HIPing. A cross section of the turbine disk after HIPing is shown in Figure 4. In this figure, the capsule has been removed from the HIPed piece on the right by chemical processing.

Turbo Pump Impeller

The core of the pump impeller shown in Figure 5 was produced by selective laser sintering (SLS) of stainless steel powder. The Ti-6Al-4V powder and

Figure 3. *Capsule before HIPing*

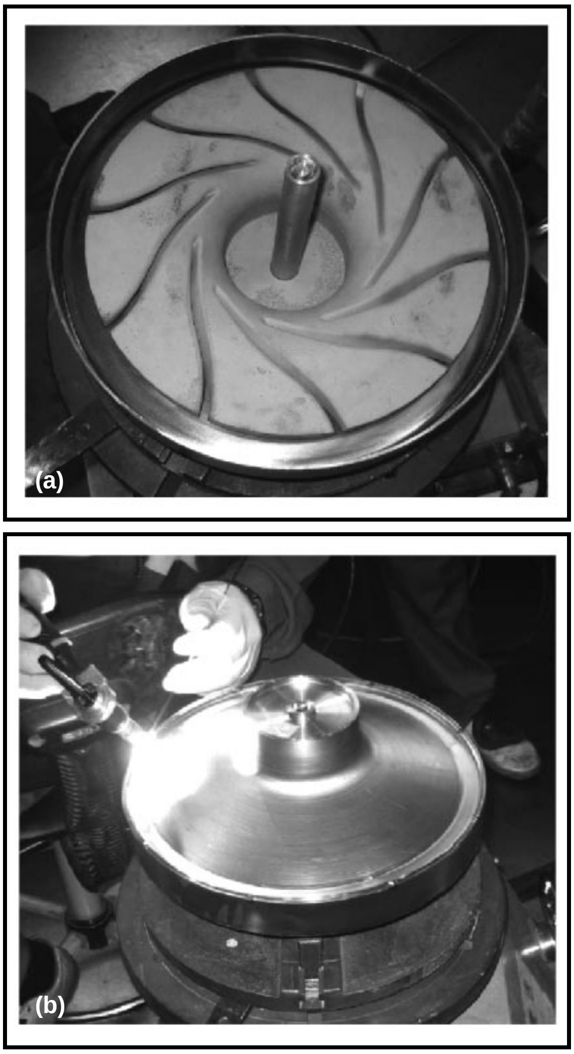


Figure 5. *Core of turbo pump impeller (a) after SLS, and (b) encapsulated for HIPing*

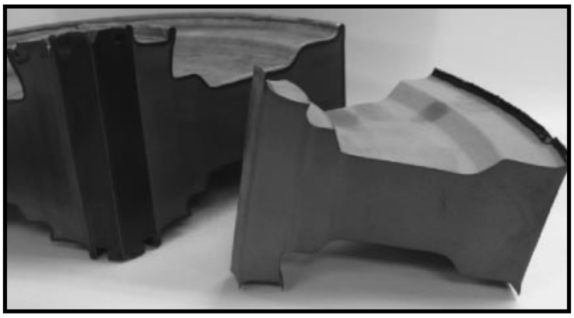


Figure 4. *Cross section of turbine disk after HIPing*

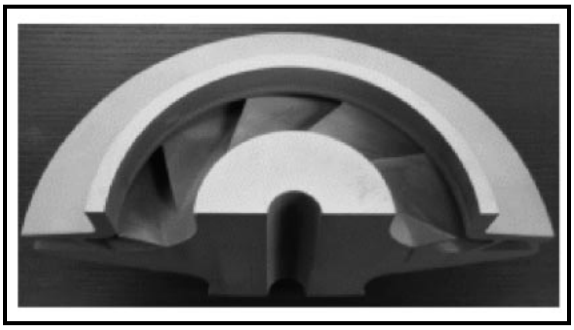


Figure 6. *Section of turbo pump impeller after removal of capsule*

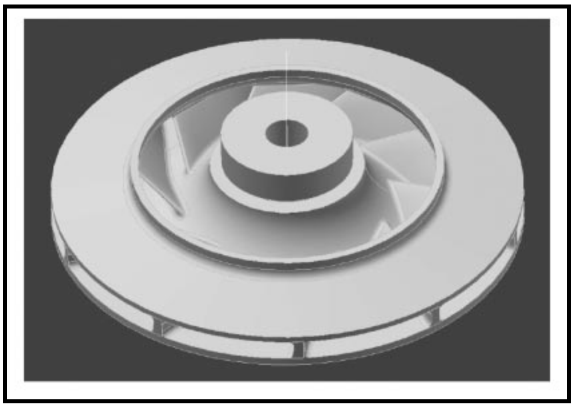


Figure 7. *Complete turbo pump impeller*

the several cores were contained in a capsule made of jointed sheet steel (Figure 5) and HIPed. Figure 6 shows a section of the turbo pump impeller after the capsule has been chemically removed, and a complete impeller is shown in Figure 7.

HIP SIMULATION

The turbine disk and the turbo pump impeller are the examples used to describe the HIPing simulation.

Turbine Disk

Figure 8 shows the dimensions of the turbine

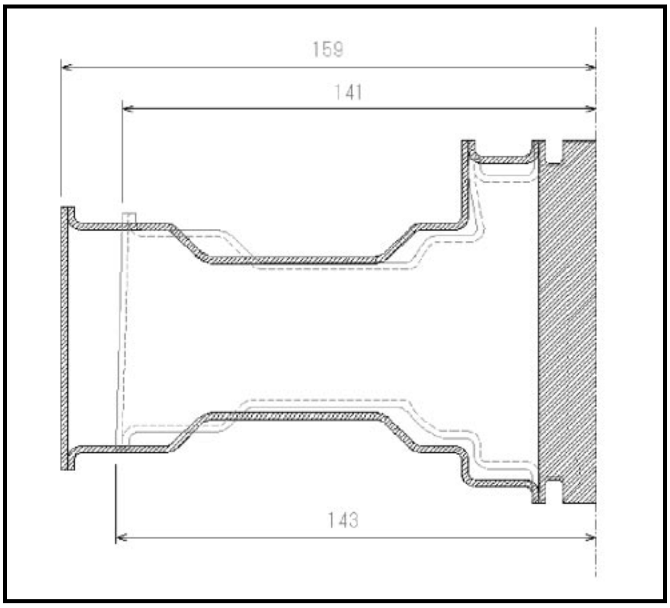


Figure 8. Comparison of turbine disk dimensions before and after HIPing. Dimensions in mm

disk before and after HIPing. The dimensions were determined by means of a three-dimensional (3D) measuring machine.

After HIPing, the turbine disk radius was reduced by 18 mm (from 159 mm to 141 mm) on the upper face and by 16 mm (from 159 mm to 143 mm) on the lower face. Using the material properties obtained from the uniaxial compression test, a HIPing simulation was performed using the MSC.Marc program. Figure 9 shows the results of the analysis for longitudinal deformation. In the figure, "Inc. 413" denotes the number of calculation increments, "lcase4" refers to "load case 4" at the end of the HIPing load history, and Y is the amount of compression in the radial direction of the turbine disk.

HIP simulation resulted in a maximum deformation of 18 mm which is in general agreement with the actual measurements. Considering the likely presence of irregularities in capsule construction and in non-uniform powder density, this result confirms the viability of the HIPing simulation model.

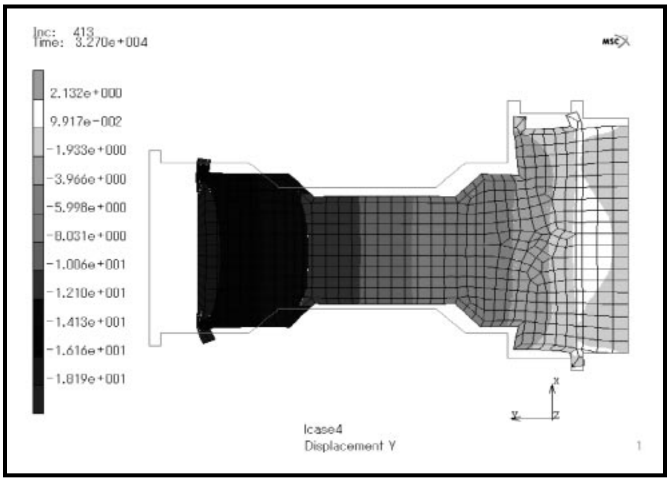


Figure 9. Dimensional comparison for turbine disk in radial direction before and after HIPing

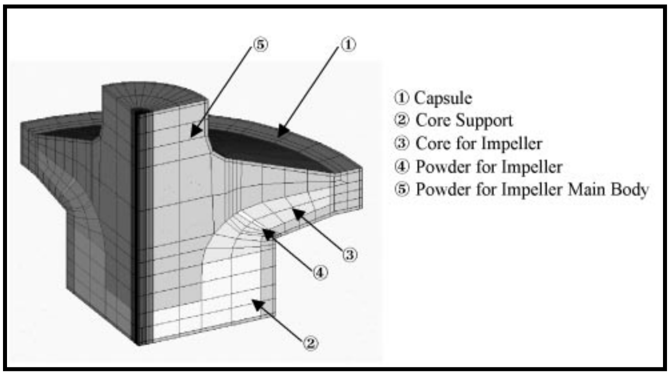


Figure 10. Analytical model for turbo pump impeller

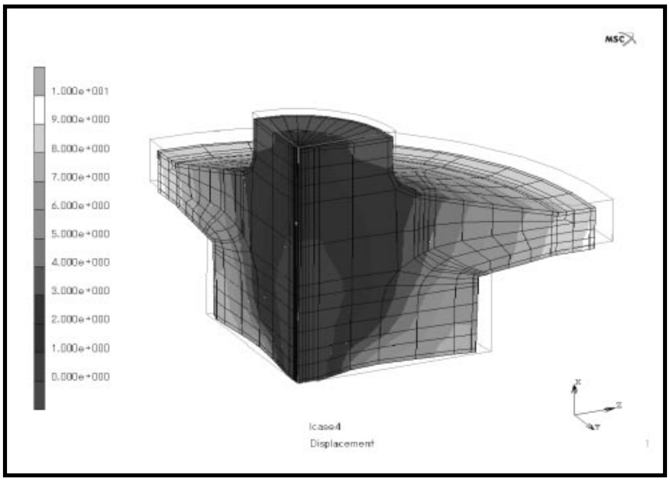


Figure 11. Sample of analytical results for displacement distribution

Turbo Pump Impeller

The analytical model is shown in Figure 10. The capsule, core, and powder are represented using the 3D solid element. Figure 11 shows representative analytical results for the displacement distribution. This evaluation was made by comparing the analytical results with the actual product dimensions. In this figure, displacement refers to the total compression in each direction (x, y, z).

SUMMARY

The objective of this study was to develop a model to simulate HIPing utilizing properties derived from uniaxial tests on materials of differing relative densities. The methods used to calculate the material properties are explained and the input data required for the simulation cited. Results of the HIPing simulation model for a titanium alloy are in reasonable agreement with those measured on an actual part.

FUTURE CONSIDERATIONS

We intend to conduct further tests on HIPed parts of more complex shape and compare the results with those obtained from a 3D simulation model. The goal is to increase efficiency in manufacturing and in the use of materials. It is necessary to utilize the capability of net-shape PM processing to keep the cost of manufacturing down and to make the process commercially viable. To this end, we intend to enhance accuracy in the analysis and to improve our production techniques.

REFERENCES

1. Theory and User Information "Powder Material", MSC.Marc 2005 r3 User's Guide, Volume A, pp. 478–480, MSC Software Corporation, Santa Ana, CA, www.mscsoftware.com.
2. S. Shima and M. Oyane, “Plasticity Theory for Porous Metals”, *Int. J. Mech. Sci.*, 1976, vol. 18, pp. 285–291.
3. T. Yabu, T. Nakagawa and A. Nohara, “Numerical Simulation of HIP Process”, *R&D Kobe Steel Engineering Report*, 1998, vol. 40, no. 4. ijpm