ENHANCED POWDER METALLURGY (P/M) PROCESSING OF UDIMET®* ALLOY 720 TURBINE DISKS – MODELING STUDIES

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Abstract

Enhanced P/M processing encompasses powder preparation, hot isostatic pressing (HIP) consolidation of powder, extrusion, isothermal forging, ultrasonic inspection, and machining technologies. This combination of technologies is being evaluated for producing P/M UDIMET alloy 720 turbine disks with improved quality at reduced cost.

The three modeling studies reported here were undertaken to support process optimization efforts to meet the project quality and cost objectives. Defect migration modeling supports the selective ultrasonic concept that can, once validated, reduce the "buy-to-fly" weight of P/M billets and also the cost of ultrasonic inspection. HIP modeling can be used to identify the most cost-effective path to achieve the desired as-HIPed density. Simulation of the machining processes used to convert a near-net shape isothermal forging to a finished disk can help to define the optimum machining sequence to minimize machining cost and disk rejects. This report describes the results of efforts to develop and apply these modeling and simulation techniques.

Introduction

The concept of enhanced P/M processing of superalloys for aircraft engine components is being undertaken as a U. S. Navy MANTECH project monitored by the NAVAIR Systems command. The project involves an extensive experimental effort by an integrated project team. The team members include: Rolls-Royce Allison, the engine manufacturer, Special Metals Corporation, the P/M billet producer, Ladish Co., Inc., the isothermal forging manufacturer, and Concurrent Technologies Corporation, the project manager and operator of the National Center for Excellence in Metalworking Technology. This project extends the work begun in the Army Comanche helicopter program [1].

* UDIMET is a registered trademark of Special Metals Corporation.

The modeling and simulation efforts reported here were undertaken to support the experimental work of the integrated project team by providing a means of rapidly evaluating processing alternatives to shorten the search for the optimum routes. Such efforts presuppose that suitable physical process models can be identified and validated prior to playing the "what if" optimization games. The three areas chosen for study using modeling and simulation techniques are material flow and defect migration, HIP processing, and machining.

Modeling Studies

Material Flow and Defect Migration

The use of fine powder (–270 mesh) enables ultrasonic inspection of the full volume of extruded billets. If no defects are created during isothermal forging, the forged disk need only be inspected in highly stressed areas. This concept, termed selective ultrasonic, can reduce the cost of ultrasonic inspection. It cannot be used for cast/wrought UDIMET alloy 720 material because the variation in grain size and composition submerges the defect signals within the background noise.

In order for the selective ultrasonic concept to be accepted by aircraft engine manufacturers, it is necessary to show that defects of concern can be detected reliably at the billet stage and tracked through isothermal forging. This is the reason for developing the defect migration model. This model requires thermophysical [1] and flow property data (upset tests on 0.5-inch diameter cylinders) for UDIMET alloy 720 in the hot working temperature range (950 – 1200 °C) at suitable strain rates (0.0001/sec to 10/sec).

Defect migration was followed using the point-tracking feature of DEFORM-2D™ going from the HIP canister to the 3:1 extrusion, and finally to the isothermal forging of the Stage 3 disk. This sequence is illustrated in Figure 1 for two widely separated planes of seeds.

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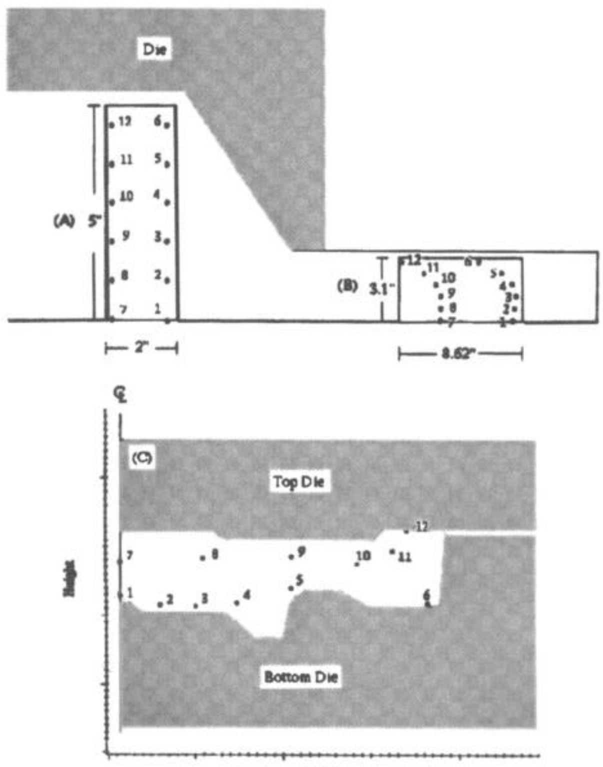

Figure 1: Defect migration simulation – A) HIP billet, B) 3:1 extrusion, C) Stage 3 disk

These planes were chosen to have the maximum separation while ensuring that the seed particles remain in the disk after isothermal forging. Points 1, 6, and 12 may have actually reached the surface.

In order to verify the numerical modeling techniques used to describe the material flow during extrusion and isothermal forging, a seeding experiment was devised. Alumina and silica particles (150 to 1000 μm in diameter) were deposited in a planar array of several layers in a HIP canister that was then extruded and sectioned. Special Metals Corporation used an ultrasonic immersion technique to find the seed particles after extrusion. A comparison of the defect migration predictions with the ultrasonic measurements, Figure 2, shows that the model appears to be a valid representation of these processes.

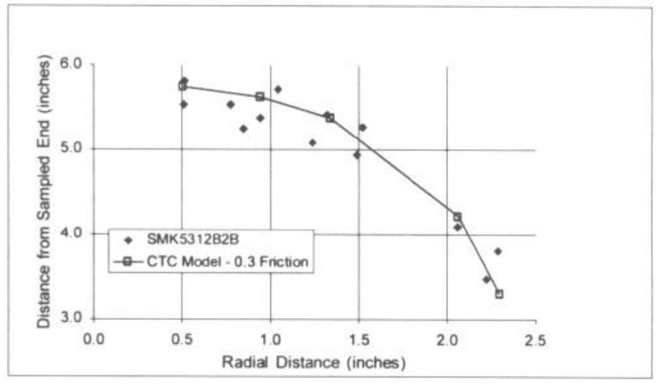

Figure 2: Comparison of predicted (finite element model) versus observed (SMK5312B2B) seed locations following HIPing and 3:1 extrusion

The curvature of the initially straight lines of seed particles (edge view) after extrusion, Figure 1B, matches results for cold extruded billets [2]. The validity of these results for extrusion, and ultimately for isothermal forging, depends on the validity of the assumptions. The defects of concern in UDIMET alloy 720 are likely to be refractory oxides. In modeling the movement of these particles it has been assumed that they (1) do not impede the flow and (2) do not change or interact with the superalloy powder particles. Based on extrusion results obtained to date, these assumptions seem reasonable. The final verification of the defect migration model will involve ultrasonic inspection, metallography, and comparison with model predictions for the disk shown in Figure 1C.

The existence of a valid defect migration model will enable a more efficient usage of billet material. If an inclusion (detected in the extruded billet) could end up in a highly stressed region of the disk, the location of the mult (within the billet) can be changed to prevent this from happening. This type of prescreening approach can avoid investing effort in a mult that could eventually be a discarded disk. The model will also be of use for detecting defect migration of particles producing ultrasonic signals below the threshold level of acceptance.

HIP Modeling

Although hot isostatic pressing (HIP) is an intermediate processing step within the enhanced P/M processing framework, considerable cost savings can be achieved through an optimization of the HIP process. The production HIP cycles used in industry are designed to attain the highest possible final density. However, since other processing steps (i.e., extrusion and forging) will be applied to the material during enhanced P/M processing, a density less than ~100% after HIP may be optimal. The goal of this effort is to develop an accurate HIP model for UDIMET alloy 720, so that the final density and microstructure can be accurately predicted. Using this model will allow an engineer to tailor the HIP cycle specifically for an application, thus reducing trial and error efforts and secondary operations.

The HIP model used in this program is based on a viscoplastic constitutive equation previously suggested for describing the densification of metal powders during HIP [3,4]. The powder aggregate is modeled as a compressible continuum with the following macroscopic potential ($\hat{\phi}$) describing its deformation

$$\hat{\phi} = S^2 + b(\rho)p^2 - c(\rho)s^2 = 0 \qquad (1)$$

where S is the magnitude of the deviatoric stress tensor, p is the pressure, and s is a measure of the deviatoric stress in the powder particle. In addition, $b(\rho)$ and $c(\rho)$ are functions of the relative density, ρ, and the form of these functions are determined by experiment.

To fully specify powder properties in the HIP model, one needs to determine the flow behavior of the powder particles, the functional forms of $b(\rho)$ and $c(\rho)$, the specific heat as a function of temperature for the fully dense powder, and the thermal conductivity of the powder as a function of both temperature and density [5]. Previously, a large set of HIP tests were required to calibrate the density dependence of the model, i.e., establish the functional form of $b(\rho)$ and $c(\rho)$. In the current project, these functions are determined using a smaller initial set of experiments and the forms of $b(\rho)$ and $c(\rho)$ based on other data from powders that have already been calibrated. The constants used in these functions are optimized for UDIMET alloy 720. This preliminary model will be used to prescribe additional HIP experiments to refine and validate the model.

The flow behavior of the powder is determined through a series of high temperature, constant strain-rate compression tests on samples over a range of density. Partially dense samples are obtained from interrupted HIP cycles and are used to calibrate the density dependence of the model. The partial HIP experiments also provide a means of validating the model after calibration. The thermophysical properties of the fully dense powder compact are normally determined using differential scanning calorimetry (specific heat) and the laser flash technique (thermal diffusivity). The density dependence of the thermal diffusivity must also be measured and is included in the model.

The test specimens for establishing the flow behavior of the powder are usually machined from as-HIPed material. However, in this case, enhanced P/M processed (i.e., HIPed, extruded, and forged) material was available and was used to save both costs and time during the initial model calibration. The experimental result of a series of compression tests on these fully dense UDIMET alloy 720 samples is shown in Figure 3.

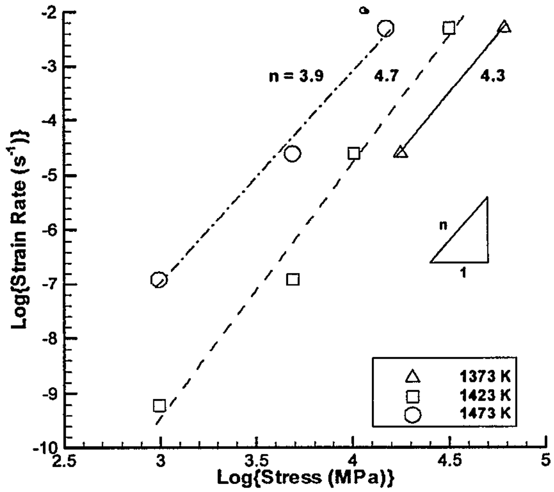

Figure 3: Creep stress exponent dependence on temperature for UDIMET alloy 720

A power law creep model, equation (2), was used to analyze the test results

$$\dot{\varepsilon} = A\sigma^n \exp\left(\frac{-Q}{RT}\right) \qquad (2)$$

where $\dot{\varepsilon}$ is the strain rate, A is a material constant, σ is the stress, n is the creep stress exponent, Q is the activation energy, R is the gas constant, and T is absolute temperature. Using the steady state results (true stress vs. true strain at constant strain rate) at different temperatures, the creep stress exponent can be determined. A least squares linear curve fit of the creep data for temperatures of 1100 °C, 1150 °C, and 1200 °C results in n ~ 4. In a similar fashion, the creep activation energy can be determined using the same set of compression tests as shown in Figure 4.

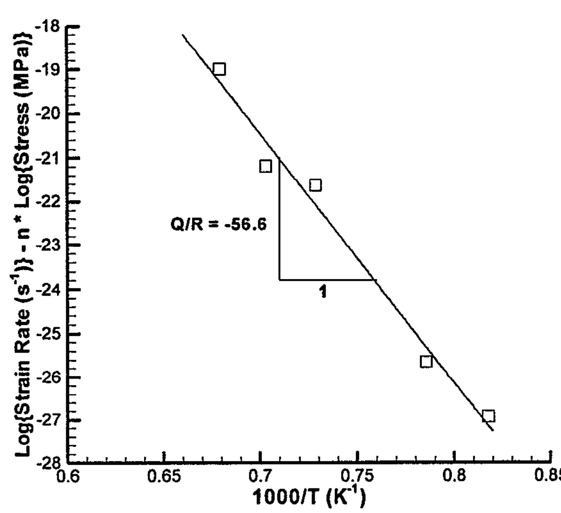

Figure 4: Creep activation energy for UDIMET alloy 720

In this case, the slope represents $-Q/R$, therefore Q= 470 kJ/mole. Finally, the material constant A is evaluated by plotting $\dot{\varepsilon}\exp(Q/RT)$ against $A\sigma^n$ on a log-log scale and determining the slope, which results in A = 2.0E+08. Additional testing will be required to more accurately establish these values for UDIMET alloy 720 over the full density range of interest. However, comparing the experimental data with the predictions of an ABAQUS™ simulation for these parameters shows good agreement for $\dot{\varepsilon}$ from 0.0001/sec to 0.1/sec, Figure 5.

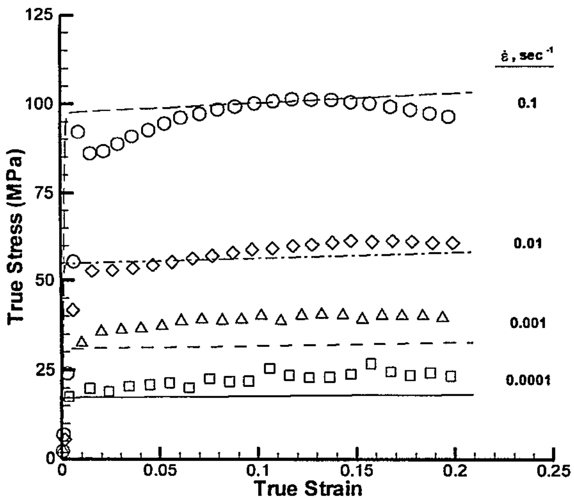

Figure 5: Comparison of experimental data (T = 1423 K) and ABAQUS simulation

Normally, the thermophysical property data are obtained from untested specimens machined from the set of HIP tests used to calibrate the model. Since the number of initial HIP experiments has been minimized in this case, another source for this information needed to be found. During the previous MANTECH program [1] on UDIMET alloy 720, measurements were made for specific heat and thermal conductivity as a function of temperature for fully dense material (HIP and extruded). The data were extrapolated to 1422 K for use in the HIP model (Figures 6 and 7).

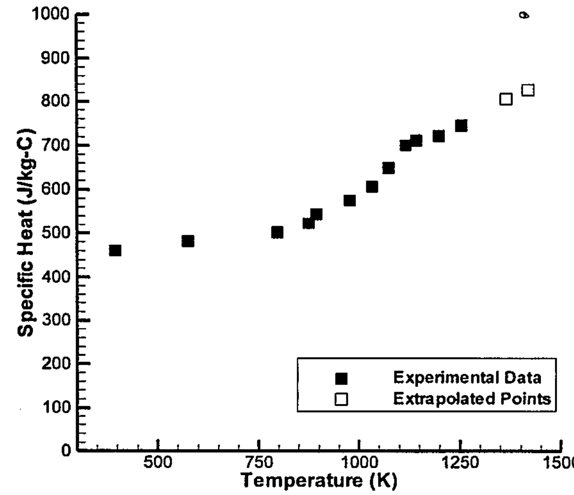

Figure 6: Specific heat as a function of temperature for UDIMET alloy 720

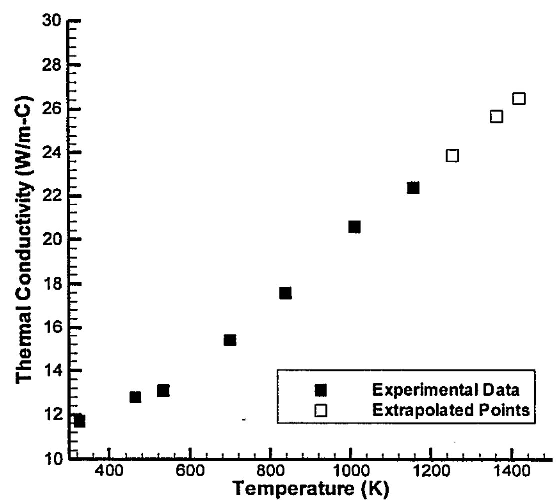

Figure 7: Thermal conductivity as a function of temperature for UDIMET alloy 720

The density dependence of the thermal conductivity for UDIMET alloy 720 is a required input of the HIP model. An estimate of this dependence was determined using thermal conductivity data for another Ni-based superalloy powder. Figure 8 shows the measured data for a range of temperatures and densities as well as the fitted equations used to interpolate the data. The exponential form of the curve fit worked well over the range of the data, since only the pre-exponential term varied with temperature. The following general form of the curve fit equation was used to scale the thermal conductivity (k) of fully dense UDIMET alloy 720 to reflect the influence of porosity

$$k = C(T) * \exp(4.0 * \rho)$$

where $C(T)$ is the temperature dependent term and ρ is the relative density. These estimated properties are suitable for the

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preliminary HIP model, but may be refined, if necessary, for the final model.

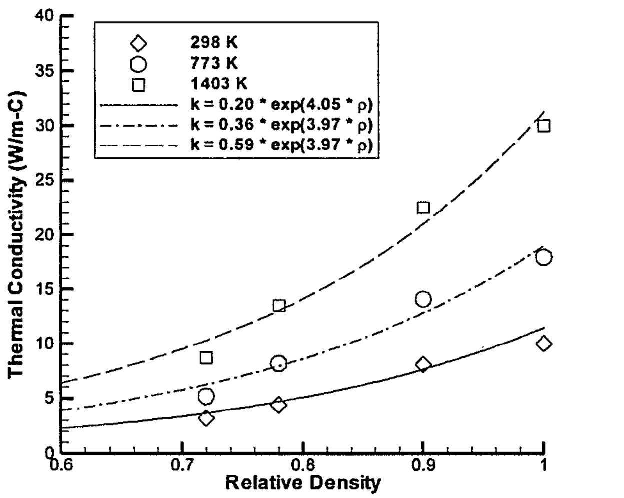

Figure 8: Thermal conductivity as a function of temperature and density for a Ni-based superalloy

The densification rate during HIP is a strong function of both temperature and pressure. Therefore, the HIP conditions used to calibrate the model must be carefully specified to allow a range of final densities to be produced within a reasonable HIPing time. Once this HIP cycle has been determined, a series of interrupted HIP experiments are performed to produce specimens for further testing as well as to provide data for the model calibration.

Since a goal of this effort is to develop an accurate HIP model with as few experiments as possible, the initial attempts to determine a suitable partial HIP cycle were used to calibrate the preliminary HIP model. Figure 9 shows the model predictions and the experimental data point for the specified HIP cycle also shown. The preliminary model uses the following forms for the functions $b(\rho)$ and $c(\rho)$

$$b(\rho) = b_1(1-\rho)^{b_2}$$

$$c(\rho) = \rho^{c_1}$$

with the constants from a previously calibrated Ni-based superalloy as an initial estimate. The model used to predict the densification curve shown in Figure 9 was adjusted for UDIMET alloy 720 by scaling the parameter b_1 in order to agree with the data. This preliminary model was used to determine the partial HIP cycle parameters and additional HIP experiments required for model verification. These experiments are currently being performed.

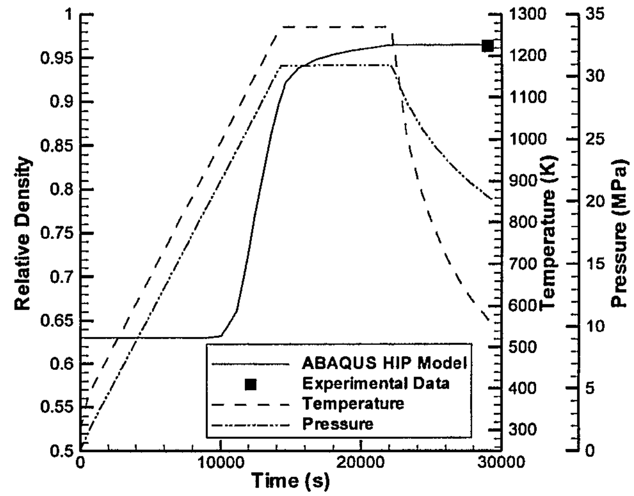

Figure 9: Relative density as a function of time for superimposed HIP cycle conditions

Modeling of Residual Stresses and Distortions during Heat Treatment and Machining

This effort was undertaken because of the engine manufacturer's prior experiences with distortion occurring during machining of cast/wrought UDIMET alloy 720. Thus, distortion is caused by the redistribution of residual stresses resulting from differential cooling rate throughout the part during quenching. Subsequent aging treatments could reduce, but do not necessarily eliminate, these residual stresses.

A general non-linear finite element code (ABAQUS) was used to simulate the cooling behavior, predict residual stresses, and then model machining through removal of groups of elements. The first step in this method is to make a suitable mesh for the disk geometry. The second step is to simulate the quenching operation. This involves specifying a temperature-dependent, convection coefficient distribution on the disk surfaces and conducting a coupled thermo-mechanical analysis. Once the thermal simulation is complete, the residual stress distribution is available. After this, distortions are estimated during the simulated machining step. The removal of groups of elements changes the stresses in order to maintain static equilibrium. As it is currently configured, stress relaxation and the build up of residual stress due to the action of machining tools are not included in the model. Also, the disk is not fixtured or constrained during the simulated machining (removal of elements).

Figure 10 shows the forged geometry (Forged Shape) of the Stage 3 disk enclosing three intermediate machined shapes (M/C Shape 1, 2, and 3). Three operations are used to transform the forged shape to the final net shape, M/C Shape 3 (region 17). M/C Shape 1 results from removing regions 1 through 8; M/C Shape 2 from removing regions 9 through 15; and M/C Shape 3 from the removal of region 16.

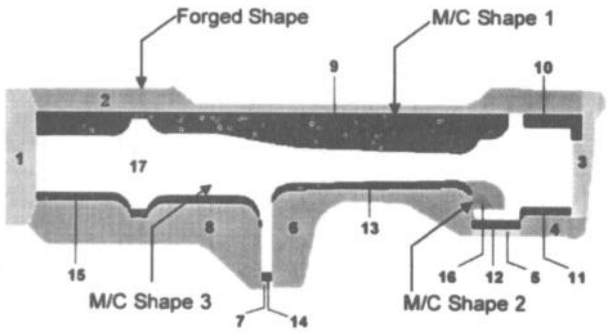

Figure 10: Shapes for disk : Forged and machined shapes

In an effort to validate the machining model and to compare the measured residual stress levels in P/M and cast/wrought UDIMET alloy 720, Moiré fringe strain measurements were made. These measurements ranging from −70 to −120 ksi showed that the circumferential and radial stresses were compressive and similar in magnitude to the average stresses for a disk. There appeared to be no significant difference in average residual stresses between P/M and cast/wrought UDIMET alloy 720. A comparison of the model predictions and the measured stresses are given in Figure 11.

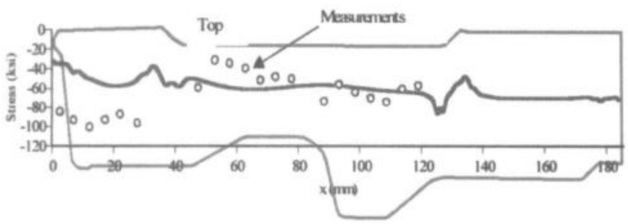

Figure 11: Comparison of Moiré fringe circumferential residual stress measurements and FEM predictions for the top surface for a cast wrought stage 3 disk

The best agreement is in the thinnest section near mid-radius. At the rim, the model predicts significantly lower stresses than were measured. The finite element predictions typically underestimated the Moiré fringe measurements by 15 to 50 percent. Experiments are currently underway to identify the source(s) of this disparity. Mesh size effects, the steepness of the stress gradients near the surface, the degree to which the thermal analysis represents the actual cooling conditions, and the surface preparations techniques for the Moiré fringe measurements, all could be contributors.

The engine manufacturer has set dimensional requirements for specific locations on the intermediate machined shapes in order to ensure that the final shape will be within tolerances. As an illustration, six locations were selected on the lower surface of the M/C Shape 1. The predicted vertical positions are compared to the specifications in Figure 12. The results show that predictions for locations 1, 2, and 6 are within the 0.005-inch tolerance while those for 3, 4, and 5 are out of tolerance. The results presented in Figure 12 are intended to illustrate the use of the machining model and are considered to be preliminary until they can be verified with actual machining data.

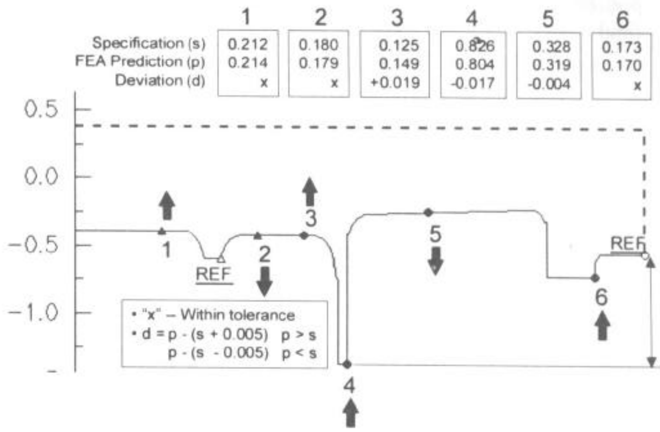

Figure 12: Specification and predicted locations for the bottom surface of M/C Shape 1. Specified tolerance limits (+/- 0.005 inch)

Conclusions

Based on the modeling and simulation approaches used to study defect migration, HIPing, and machining of P/M UDIMET alloy 720 turbine disk material, the conclusions are:

1. A model of oxide particle migration during HIPing and extrusion based on DEFORM-2D software provides accurate predictions of particle movement.
2. A model for describing the as-HIPed density as a function of HIP processing parameters has been developed for defining cost-effective processing.
3. A model of disk machining processes has been developed that has potential for identifying operation sequences to minimize distortion.

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