Parallel Optimization of Forging Processes for Optimal Material Properties

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Abstract. Validated, internal state variable constitutive models are developed to model the complex multi-stage forging process and predict the final forging strength and microstructure. Optimization methodologies are then used on a high performance, parallel computer to design the forging dies and temperatures that would meet minimum and maximum strength requirements and result in maximum strength uniformity. Each node on the parallel computer solves a unique finite element simulation including parametric meshing, post-processing and metric determination. Nine shape parameters and one process parameter (temperature) are optimized to reduce strength non-uniformity. The final process design, based on over 360 finite element simulations, meets all material requirements and results in a near uniform strength part.

INTRODUCTION

Designing gas reservoirs to survive the long term exposure to hydrogen and tritium gas is a difficult and unscientific process. A typical high pressure gas reservoir is shown in Fig. 1. Research has shown that the final material state is critical to reducing the material degradation that has led to past reservoir problems. Only a forging process has been able to produce the required material state. Rigid constraints on long-term gas compatibility necessitates strict requirements on forged material strength, uniformity of strength, grain size and grainflow. The limited number of materials able to resist the hydrogen embrittlement effects results in steels that must be warm-worked to achieve the desired strength levels. Unlike most automotive and aerospace forgings, these few materials cannot be heat-treated after forging to increase strength levels. Instead a complex multi-stage forging process consisting of as many as seven forging stages is required to produce the required strength levels and grainflow directions. (A typical gas reservoir forging is shown in Fig. 2.) The result is a very costly and time consuming, trial-and-error forging process development. Computer modeling and optimization are used to significantly reduce time and costs of process design and to optimize the final material state. The ultimate goal of computer modeling the forging process is to reduce procurement times from as much as 30 months to as little as 2 months with associated reductions in costs and defects.

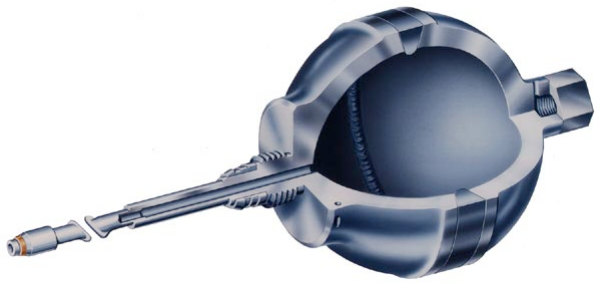

FIGURE 1. Typical Gas Reservoir

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FIGURE 2. Typical Reservoir Forging

Accurate prediction of material strength and microstructure requires complex, internal state variable (ISV) constitutive models that capture the effects of strain rate, temperature, and history dependence. These simulations employ a modified form of the Bammann-Chiesa-Johnson (BCJ) plasticity model [1,2] which accurately tracks the material state through the multi-stage forging process and can predict the recrystallization that often occurs. More details of the constitutive model and methodology for prediction of material state evolution can be found in another NUMIFORM 2004 paper by Chiesa et al.[3].

METHODOLOGY

Computer optimization of the forging process can require from several hundred to several thousand, complex, finite element simulations. Performing this many simulations on a serial computer can take many days which delays the design and procurement process. This problem is ideally suited for parallel computers since many of these simulations can be performed simultaneously. This application is slightly different than the typical multi-million element simulation performed on a large parallel computer where hundreds of processors are employed on the same calculation. In this application, each processor solves a unique analysis and the results from all the simulations are examined to determine which direction to proceed for the next round of analyses.

Ten different parameters were identified as potentially having a significant effect on the forged part quality. These included seven to describe the pre-form shape, two to describe the geometry of the punch and the last parameter defining the forging temperature. The external shape of the forging was assumed fixed. Definitions of the geometric parameters are depicted in Fig. 3. A further requirement on the parameters was that the preform geometry had to have a pre-specified volume. Performing automated optimization of finite element simulations in which the geometry changes requires that the mesh be definable in terms of the input parameters (i.e., a parameterized mesh) and a robust meshing program/algorithm that can automatically mesh the different geometries without human involvement. Typically, one of the most time consuming tasks in shape optimization is development of a robust automated and parameterized meshing scheme that can generate an acceptable mesh over the range of geometric parameters. Mesh generation software that utilizes paving technology is essential. The pre- and post-processing code, ANTIPASTO (AP) [4] was used in this application.

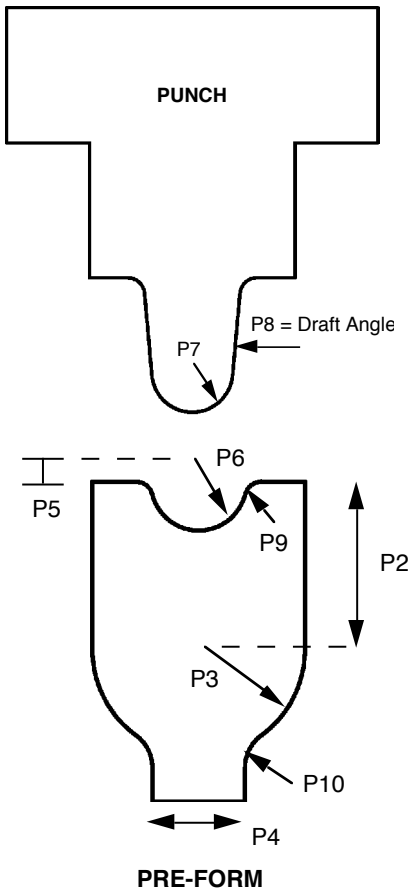

FIGURE 3. Geometric Optimization Parameters

The explicit, dynamic, structural analysis code, PRONTO2D [5], was used in this project to model the deformation and resulting material properties of the forging process. The forgings are made using a HERF (High Energy Rate Forging) process in which the punch speeds are typically 20-80 ft/sec (6.6-26.2 m/s). Since the deformation process is complete in less than

15 msec, this problem is ideally suited for explicit, dynamic codes and density scaling is not required to achieve reasonable solution times. Even though the explicit codes are very tolerant to severely deformed elements, there were some cases in which the excessive deformations caused the code to terminate prematurely. This mostly happened when the initial pre-form geometry was unrealistic. Maximum effective plastic strains in the simulations typically exceeded 200% and maximum strain rates exceeded 1000/sec in some elements. Heat conduction between the forging and dies was ignored due to the short length of time the parts are in contact. A value of 0.15 was assumed for the Coulomb friction between the forging and die parts.

The BCJ plasticity model was used to model the response of the 21-6-9 stainless steel. The model incorporates strain rate and temperature sensitivity, as well as damage, through a yield surface approach in which state variables follow a hardening minus recovery format. Both dynamic and static recovery mechanisms are included in the kinematic and isotropic hardening state variables. The model has recently been extended to predict the evolution of grain size, recrystallization and their effect on the flow stress. Constitutive parameters for 21-6-9SS were determined by a nonlinear, least-squares fit to high temperature, high rate, large strain, compression data. A single set of parameters was used to model the material response for temperatures from 70F (21C) to 1800F (980C) and for strain rates from 0.001/sec to 100/sec. Material response above 100/sec is extrapolated by the model due to lack of high rate, high temperature Hopkinson bar data for this material.

A derivative-free, fault-tolerant, global optimization technique was required to handle the complex and typically non-smooth behavior of a forging simulation. Asynchronous Parallel Pattern Search[1] (APPS) [6] was chosen mainly because it achieves a high degree of efficiency by minimizing the communication between nodes. Like other pattern search methods, it evaluates a pattern of perturbations of design parameters about a starting point to determine the direction to find better designs. The necessary minimum number of points in the pattern is twice the number of parameters (e.g., to search for the lowest point of land would require looking to the west, to the east, to the north and to the south). To conserve resources on a busy machine we chose the minimum number of nodes, 20, for the number of design parameters we used, 10. More nodes and correspondingly more points in the pattern would have potentially lead to a faster and better solution.

Design requirements on the final part material properties specify that the forging must have a minimum yield strength of 80 ksi (552 MPa) and a maximum yield of 100 ksi (690 MPa). The material has an annealed room temperature yield strength of 50 ksi (345 MPa). In addition, in order to minimize effects of hydrogen embrittlement, the forging should have as close to uniform properties as possible (i.e., no large gradients in material strength). The problem was thus set up to optimize the ten parameters such that uniformity in material properties was maximized subject to the constraints of minimum and maximum allowed yield. This is further complicated by the need to optimize properties only over the part of the forging that would remain after final machining of the reservoir. To accomplish this, a second mesh of the final reservoir geometry was constructed and the material properties from the forging were mapped onto the reservoir mesh. The calculated values over this volume were then used by APPS to redefine parameters for the next suite of 20 simulations.

Figure 4 shows the flowchart for a simulation performed all on a single node (there are 19 other simulations being performed simultaneously on other nodes). Based on the parameters determined by the optimization program, APPS, the mesh generator program, AP, automatically generates a new mesh as shown in Fig. 5a. PRONTO2D reads this new mesh and the forging temperature and performs the structural analyses as shown in Fig. 5b and 5c (Fig. 5b is at an intermediate time and 5c is at the end of the forging simulation.) A post-processing program, ALGEBRA [7], reads the internal state variables from the BCJ model in the PRONTO2D output file and analytically calculates the room temperature yield strength values. These results, shown in Fig. 6a are then mapped by the post-processor, AP, onto a mesh of the final machined part as shown in Fig. 6b. A final code then reads this information and calculates the metrics to be used by APPS to generate improved parameters for the next evaluation. The metrics measure the strength uniformity of the part using the coefficient of variation in a specified region and included a penalization of the minimum strength constraint.

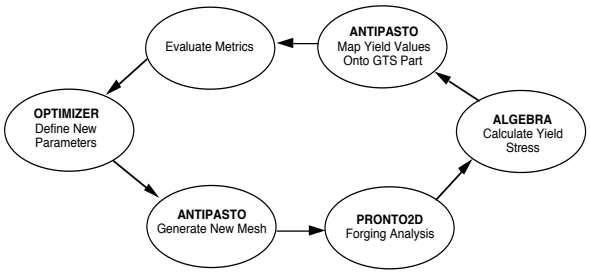

FIGURE 4. Flowchart for Simulation on a Single CPU

[1] APPS is freely available at http://software.sandia.gov/appspack

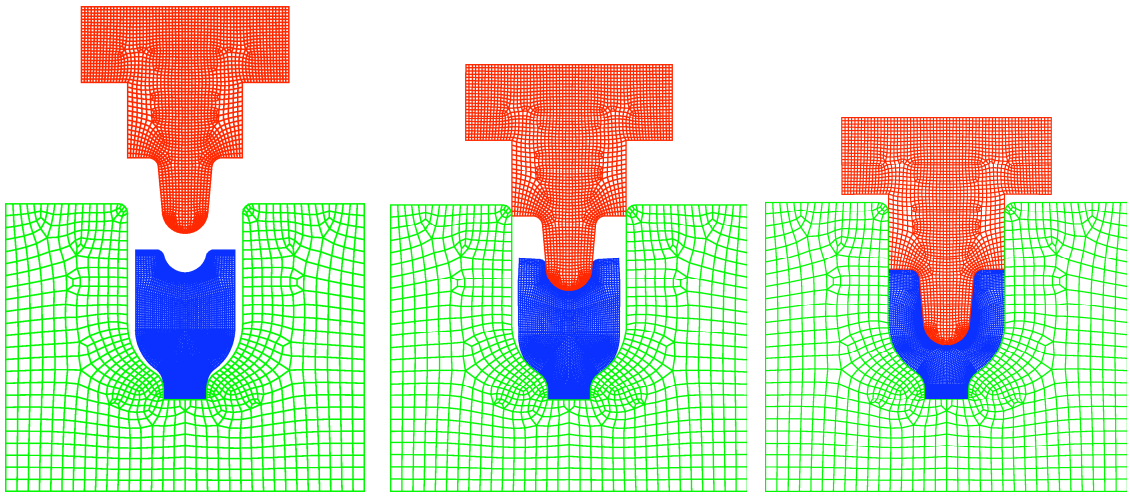

FIGURE 5. Sample Deformed Mesh Plots Generated on CPlant

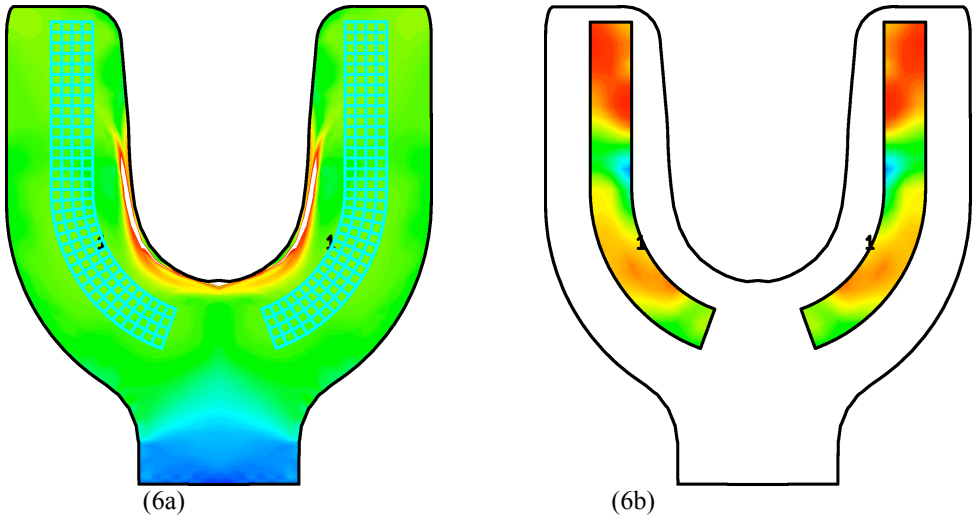

FIGURE 6. Contours of Yield Strength on a Forged Part (6a) and Remapped Onto Final Machined Part (6b). (Note: Contour levels were changed between Figures 6a and 6b)

RESULTS

The simulations were performed on a parallel Unix computer named CPlant at Sandia National Laboratories. The platform consists of approximately 400 Dec Alpha processors running at 600 MHz. The parallel computer has recently been replaced by a new parallel computer using Intel Xeon processors running at 3.6 GHz. The ten parameter optimization model required twenty CPlant nodes (the optimizer evaluates a perturbation of each parameter and then uses the results from the twenty simulations to determine the most promising direction to head for the next iteration). Initial estimate and bounds for the ten parameters were determined and the mesh was parameterized to allow automatic mesh generation over this parameter space. A final optimized process was obtained after 18 iterations (for a total of 360 finite element solutions). The total processing time on CPlant was 508 minutes. This compares to approximately 45 minutes to perform

a single finite element simulation on a high speed SUN workstation. This represents essentially 1/30th of the time it would have taken in a completely serial calculation. This speed-up is super-linear mainly due to the efficiencies in the procedure to communicate infeasible search directions and thus eliminate unnecessary calculations.

The results from the optimization showed that several of the parameters were very significant in determining the final part quality and identified several of the other parameters as having little effect on the results. The process was optimized to result in minimum variation in material strength in the machined part subject to the minimum and maximum strength constraints. The final optimized process produced a variation of plus or minus 1 ksi with an average yield strength of 82 ksi. The final design had a strength uniformity value of 0.094 and passed the minimum strength requirements. This reflects a great improvement compared to the 2.692 value computed for the initial design (which reflects its inhomogeneity and a penalty, based on its failure to meet the minimum strength requirements). Although there was a large difference between the initial and final metrics, it was surprising that the values of the ten parameters changed minimally (less than 1%). It appears that the algorithm had difficulty in locating a global minimum and instead chose to optimize about a local minimum point. This may have been because the feasible region due to the minimum strength criterion may have been very small or because the initial starting point was very close to an optimized design.

SUMMARY

Computer simulations were applied to optimize the final material properties of forgings. Complex, internal state variable constitutive models are necessary to predict the complicated stress states occurring during high temperature, multi-stage forging processes. Parallel computing methodologies significantly reduced the process design time and resulted in a near optimal final design.

ACKNOWLEDGMENTS

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REFERENCES

1. D. J. Bammann, M. L. Chiesa, M.F. Horstemeyer and L.I. Weingarten, "Failure in Ductile Materials Using Finite Element Methods", *Structural Crashworthiness and Failure*, edited by N. Jones and T. Wierzbicki, 1993, Elsevier Press, pp. 1-54.
2. D. J. Bammann, M. L. Chiesa and G. C. Johnson, "Modeling Large Deformation and Failure in Manufacturing Processes", Proceedings of the 19th International Congress of theoretical and Applied Mechanics, Kyoto, Japan, edited by T. Tatsumi et. Al., 1997, Elsevier Press, pp. 359-376.
3. M. L. Chiesa, B. R. Antoun, A. A. Brown, J. T. Ostien, D. J. Bammann and R. A. Regueiro, "Prediction of Final Material State in Multi-Stage Forging Processes", to be published, NUMIFORM 2004, June, 2004.
4. P. E. Nielan, K. J. Perano and W. E. Mason, "ANTIPASTO: An Interactive Mesh Generator and Pre-Processor for Two-Dimensional Analysis Programs", Sandia National Laboratories Report SAND90-8203, May, 1990.
5. L. M. Taylor and D. P. Flanagan, "PRONTO2D – A Two-Dimensional Transient Solid Dynamics Program", Sandia National Laboratories Report SAND86-0594, March, 1987.
6. P. D. Hough, T. G. Kolda, and V. J. Torczon, "Asynchronous Parallel Pattern Search for Nonlinear Optimization", SIAM J. Scientific Computing, Vol. 23(1), June, 2001, pp. 134-156.
7. A. P. Gilkey, "ALGEBRA – A Program that Algebraically Manipulates the Output of a finite Element Analysis (EXODUS Version)", Sandia National Laboratories Report SAND88-1431, August, 1988.