OAK RIDGE
NATIONAL LABORATORY
MANAGED BY UT-BATTELLE
FOR THE DEPARTMENT OF ENERGY

ORNL/TM-2012/300

Two-Piece Compaction Die Design

October 2012

Prepared by

Ethan Coffey
R&D Staff, Dynamic Systems Analysis and Simulation

UT-BATTELLE

ORNL-27 (4-00)

ORNL/TM-2012/300

Measurement Science and Systems Engineering

TWO-PIECE COMPACTION DIE DESIGN

Ethan Coffey

Date Published: October 2012

Prepared by
OAK RIDGE NATIONAL LABORATORY
Oak Ridge, Tennessee 37831-6283
managed by
UT-BATTELLE, LLC
for the
U.S. DEPARTMENT OF ENERGY
under contract DE-AC05-00OR22725

CONTENTS

Page

LIST OF FIGURES

Figures **Page**

ABSTRACT

ORNL/TM-2010/48[1] described some results from using the finite element program ANSYS to determine the design geometry for compaction dies used to create europium oxide and tantalum control plates. Because of some discrepancies between the final drawings of the parts and the TM analyses, the models were reworked and some design modifications were made. When the mesh density was increased, increasing the number of elements in the model, especially near the corners, the maximum stresses in the corners were found to be higher than in the previous study. The dies needed to be designed with inner corner radii and interference fits that would allow the necessary compression force to create the plates but not exceed the yield strength of the material. Also, modeling was done to determine the effects of loading the dies asymmetrically in the axial direction, as this would make the plate extraction process easier while increasing the stress in the corners.

The results show that for the tantalum die, a diametrical interference fit of 0.0020 in. between the outer ring and the insert is acceptable, and the inner corner radius can be as small as 0.0035 in. The insert has an outer diameter of 6.150 in. The cavity in the insert is 3.4640 × 0.8086 ± 0.002 in. and the outer ring has an outer diameter of 8.150 in. The die is 2.960 in. deep. With these design parameters, the plate can be formed so that its edge is 0.500 in. from the top or the bottom of the die, and the maximum stress everywhere in the die will be less than the yield strength of the materials.

For the europium oxide die, the diametrical interference fit between the outer ring and the insert must be between 0.0075 and 0.0080 in. The inner corner radius can be as small as 0.0055 in. The insert has an outer diameter of 5.960 in. The cavity in the insert is 3.4552 × 1.7246 ± 0.002 in. and the outer ring has an outer diameter of 8.150 in. The die is 3.020 in. deep. With these design parameters, the plate can be formed so that its edge is 1.225 in. from the top or the bottom of the die.

1. INTRODUCTION

To create a control plate of the type used in some nuclear reactors, it is necessary to perform a powder compaction process. In this process, metallic powder is compressed at very high pressures in a die until a solid piece is formed in the shape of the die. The dies discussed in this report are made of two pieces—an insert and an outer ring— held together by an interference fit, as seen in Fig. 1.

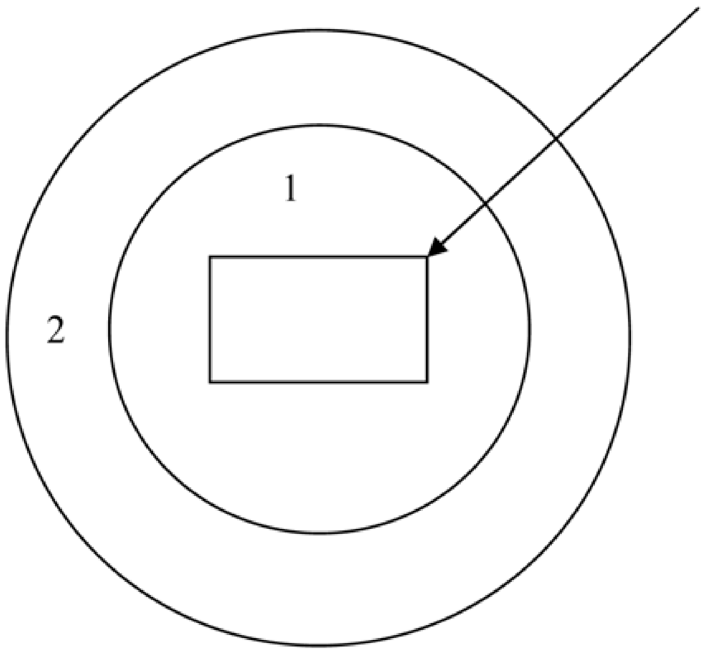

Fig. 1. Two-piece die layout. Piece 1 is the die insert and piece 2 the outer ring. The center rectangle is the die cavity.

The arrow in Fig. 1 indicates one of the interior corners of the die. Since the control plates are to be as rectangular as possible, these interior corners have very small radii, and this is where the highest stresses will occur. The stress in the corner cannot be allowed to exceed the yield strength of the insert material, as this could cause plastic deformation of the die.

Two dies were considered: one for compacting europium oxide powder and another for compacting tantalum powder.

1.1 DIE MODELS

1.1.1 Geometry

The europium oxide die insert has an outer diameter of 5.960 in. The cavity in the insert is 3.4552 × 1.7246 in., and the outer ring has an outer diameter of 8.150 in. The die is 3.020 in. deep.

The tantalum die insert has an outer diameter of 6.150 in. The cavity in the insert is 3.4640 × 0.8086 in., and the outer ring has an outer diameter of 8.150 in. The die is 2.960 in. deep.

The dimensions that have the greatest effect on the stress in the die insert corners are the cavity wall lengths. These are the nominal dimensions as given in the original TM. The effect of increasing or decreasing the cavity size is shown in Sections 2.1.2 and 2.2.2 of this paper.

The other dimensions of concern are the radius of the cavity corners and the value of the interference fit between the die insert and outer ring. These dimensions are discussed in Sections 2.1.1 and 2.2.1.

1.1.2 Materials

For both models, the die insert is made of AISI-D2-TS steel and the outer ring is 4340 steel. Thus the elastic modulus of both the insert and the outer ring is 30e6 psi and the Poisson's ratio is 0.3. The insert, which is treated to a Rockwell C hardness of 60 to 62, has a yield strength of 312 ksi; the outer ring, which is treated to a Rockwell C hardness of 28 to 32, has a yield strength of 120 ksi. During simulation, the Von Mises stress was plotted and compared with the yield strength to determine if the die would yield.

1.1.3 Model

Since the geometry is symmetrical, the dies were cut across two planes and symmetry boundary conditions were used. Figure 2 shows an example of the quarter-model of the tantalum die. The finite-element program ANSYS 12.1[2] was used, and solid brick 95 elements were used for both the die insert and the outer ring. To model the interference fit influence, the insert was modeled with the correct outer diameter and the outer ring was modeled with a slightly smaller inner diameter, forcing the pieces to overlap. Contact elements were created between the inside face of the outer ring and the outside face of the insert. This effect simulated the compression created on the insert by the interference fit with the outer ring. The mesh was created by sweeping the solids with a tetrahedral mesh. The tantalum model had about 110,000 nodes and the europium oxide model about 100,000 nodes.

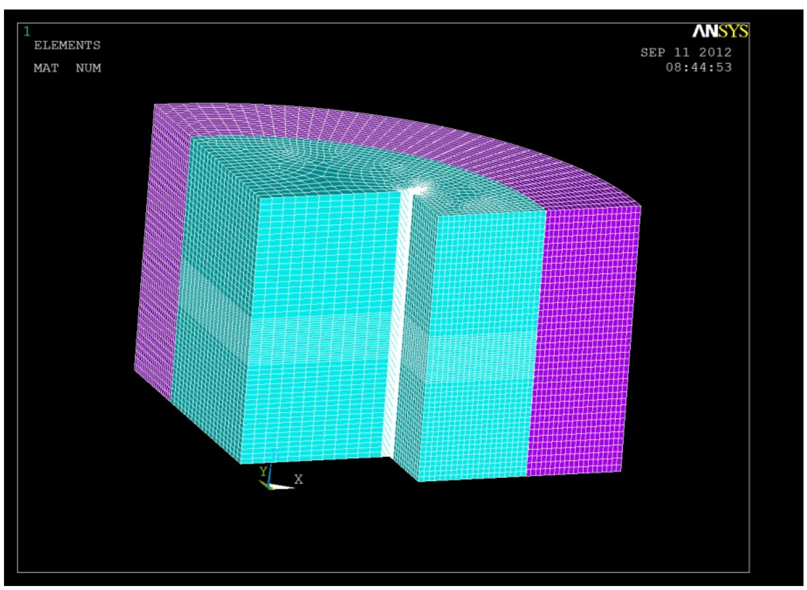

Fig. 2. Die model with increased mesh density, especially in the cavity corner.

1.1.4 Loading

The two scenarios simulated were the "no load" and the "loaded" conditions. In "no load" condition, the only influence on the stress in the die was the interference fit between the two pieces. In "loaded" condition, the die was undergoing the powder compaction process, causing a large pressure to build up along the walls of the inner cavity. The maximum compressive force was used for both dies, and it was assumed that this force caused a constant hydrostatic pressure across 0.525 in. of the die, since the final compacts were to be 0.525 in. deep. The nominal position for the applied pressure was at the center of the die, but one purpose of the tests described in this paper was to determine how much asymmetry of loading the die could handle without yielding.

For the europium oxide die, the maximum force was 240,000 lb, which created a pressure of 44,128 psi on the cavity wall. For the tantalum die, the maximum force was 100,000 lb, creating a pressure of 22,290 psi on the cavity wall (based on the nominal cavity dimensions described in Section 1.1.1).

2. RESULTS

2.1 TANTALUM DIE

2.1.1 Nominal Dimensions

In ORNL/TM-2010/48, it was shown that a 0.0035 in. radius was acceptable for the inner corner of the die insert of the tantalum die, and a 0.0020 in. diametrical interference fit between the two pieces. Figures 3 and 4 show the Von Mises stress in the tantalum die with nominal dimensions of 0.0035 in. for the inner corner radius and 0.0020 in. for the diametrical interference fit.

The largest Von Mises stress in the no load condition is about 73 ksi. In the symmetrically loaded condition, it is about 260 ksi. Both of these are well under the yield strength of 312 ksi for the tool steel used for the insert. The stress in the outer ring is also well below the 120 ksi yield strength of the 4340 steel used for that part.

In addition to stress considerations, there is some concern about the deformation of the cavity walls due to the loads on the die. In the no load condition, the maximum displacement of each side of the cavity wall is less than 0.0005 in.

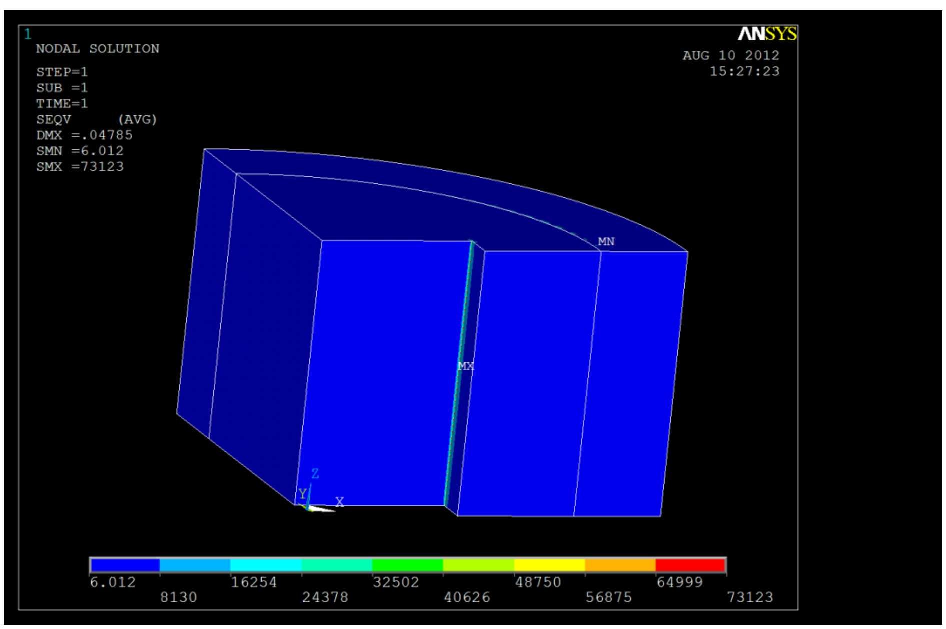

Fig. 3. Tantalum die under no load condition—Von Mises stress.

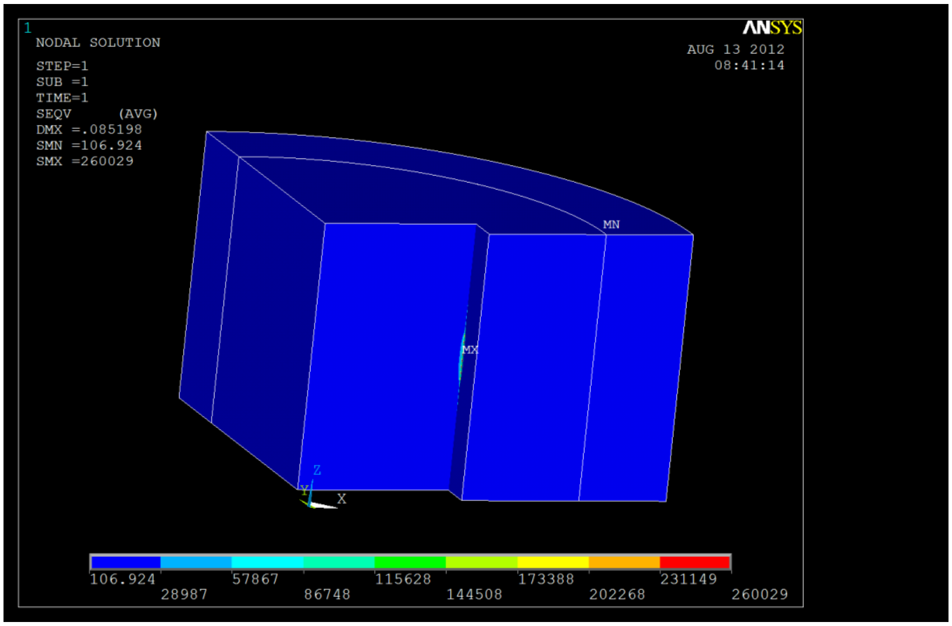

Fig. 4. Tantalum die under symmetrical load condition—Von Mises stress.

2.1.2 Cavity Size

Since the cavity size may vary as a result of manufacturing tolerances, simulations were run in which the cavity size was changed slightly to determine the effects. Each cavity wall length was increased by 0.002 in. and then decreased by 0.002 in. As can be seen in Figs. 5 and 6, these dimensional changes caused the stress at the corners to change, but it is still far from the 312 ksi yield strength of the die insert. Therefore, the cavity dimensions required for the tantalum die to stay within the bounds of these simulations are $3.4640 \times 0.8086 \pm 0.002$ in.

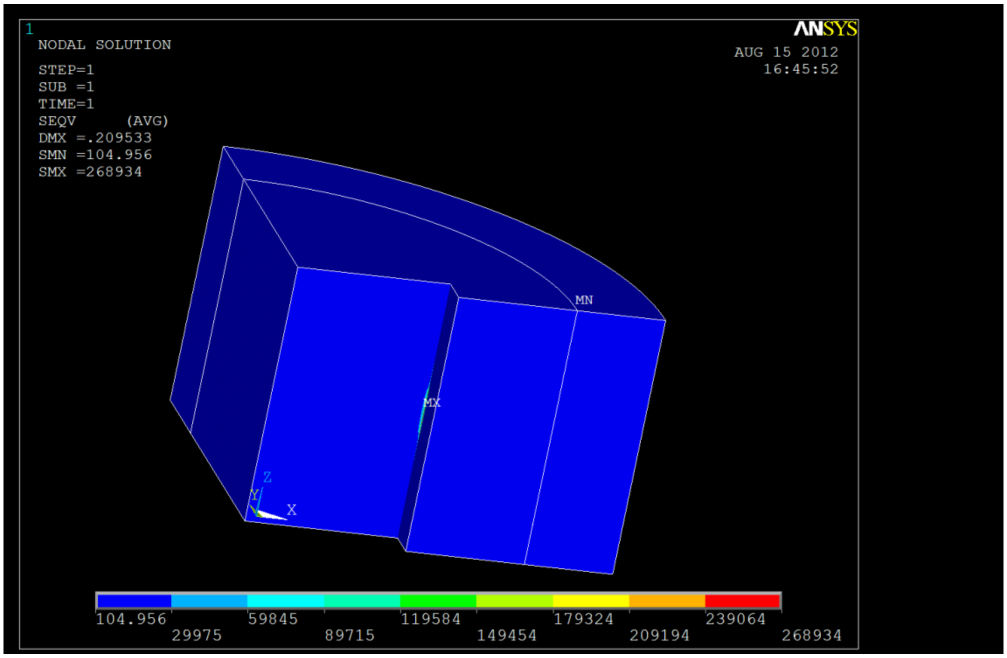

Fig. 5. Tantalum die under symmetrical load condition—Von Mises stress, smaller cavity.

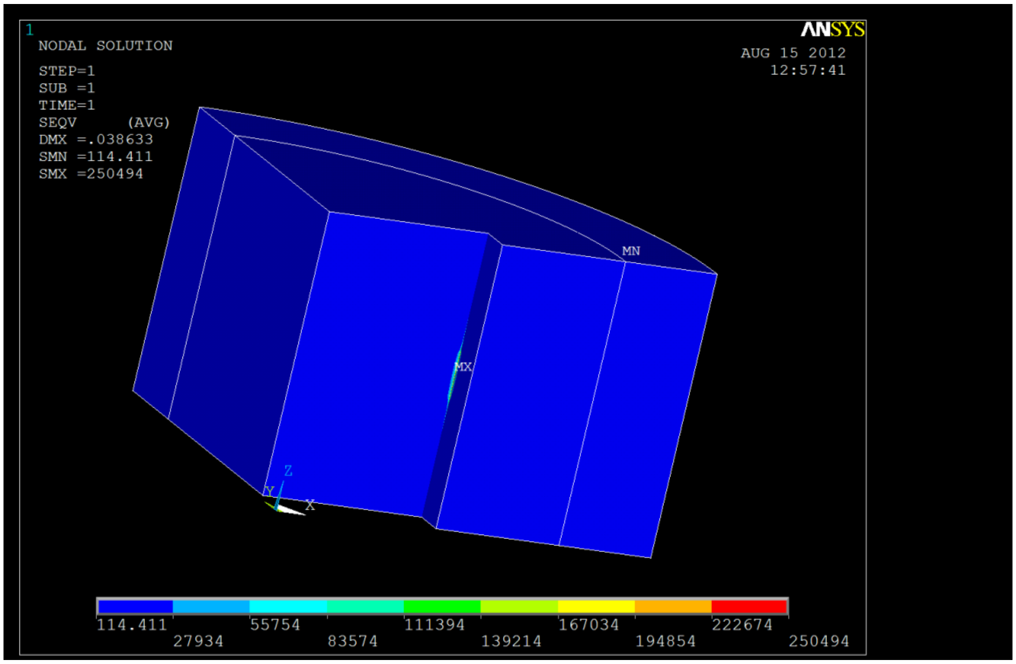

Fig. 6. Tantalum die under symmetrical load condition—Von Mises stress, larger cavity.

2.1.3 Asymmetrical Loading

The initial analyses of the tantalum die and geometry were done with symmetrical loading, meaning that the metal block would be formed in the 0.525 in. at the center of the die, as shown in Fig. 7. However, the block is easier to remove from the die if it is closer to one side. In Fig. 8, once the metal block is formed, its bottom edge is 0.500 in. from the bottom edge of the die. This is asymmetrical loading, and one goal of this simulation was to determine how asymmetrical the loading could be without yielding the die material.

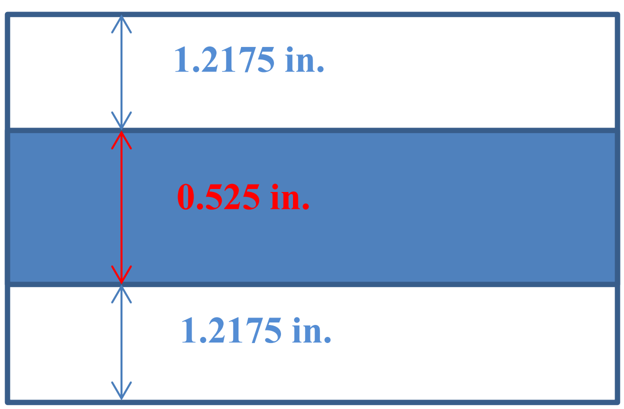

Fig. 7. Diagram showing symmetrical loading (not to scale).

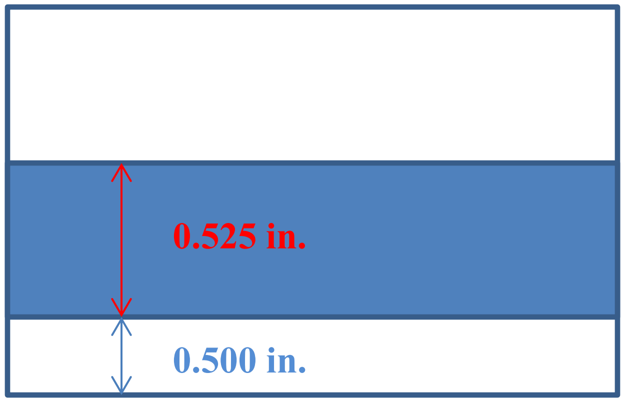

Fig. 8. Diagram showing maximum allowable asymmetrical loading (not to scale).

Figure 9 shows the Von Mises stress in the tantalum die given the "worst case scenario" in terms of stress, which includes a 3.4620 × 0.8066 in. die cavity and asymmetrical loading as depicted in Fig. 8. As can be seen in Fig. 9, the maximum stress is still below the yield strength of 312 ksi. Thus for the tantalum die with the dimensions given in this report, the edge of the metal billet can be 0.500 in. from the edge of the die without causing the die to yield, even on the outer limits of the allowable cavity dimensions.

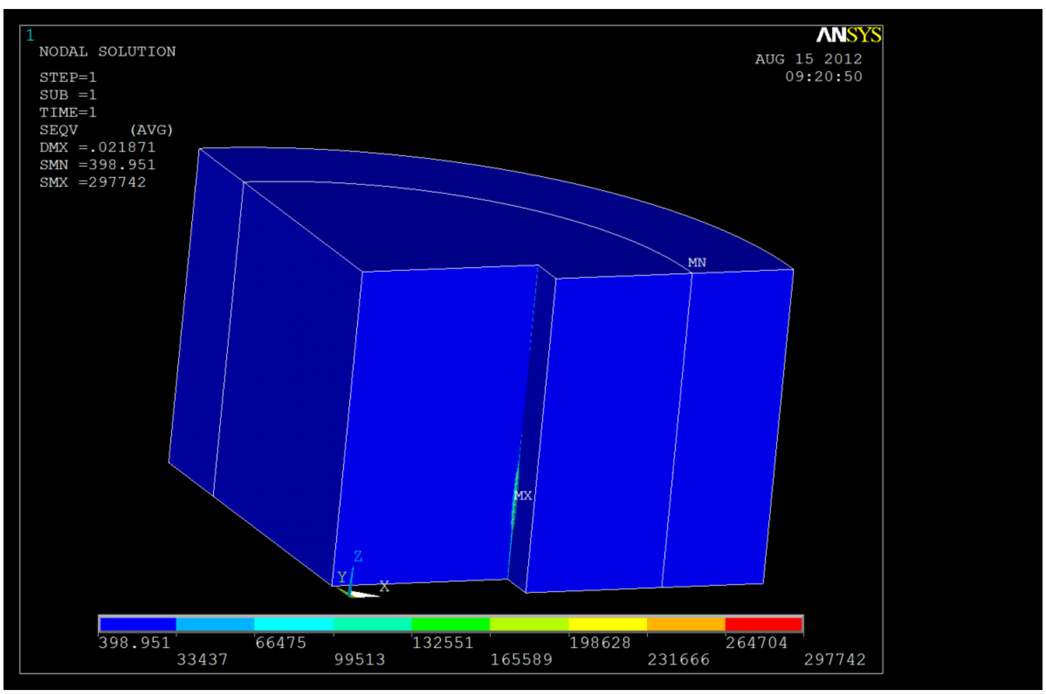

Fig. 9. Tantalum die under asymmetric load condition—Von Mises stress.

2.2 EUROPIUM OXIDE DIE

In ORNL/TM-2010/48, it was shown that a 0.0035 in. radius was acceptable for the inner corner of the die insert of the europium oxide die, along with a 0.0060 in. diametrical interference fit between the two pieces. However, further studies and a finer finite element mesh done with these dimensions found the stress at the corner to be too large. Figures 10 and 11 show the Von Mises stress in the europium oxide die with nominal dimensions, a 0.0035 in. inner corner radius, and a 0.0060 in. diametrical interference fit. As can be seen in Fig. 11, using the dimensions given in the previous TM, the stress in the die insert corner is higher than the 312 ksi yield strength of the material. Therefore, additional modeling was necessary.

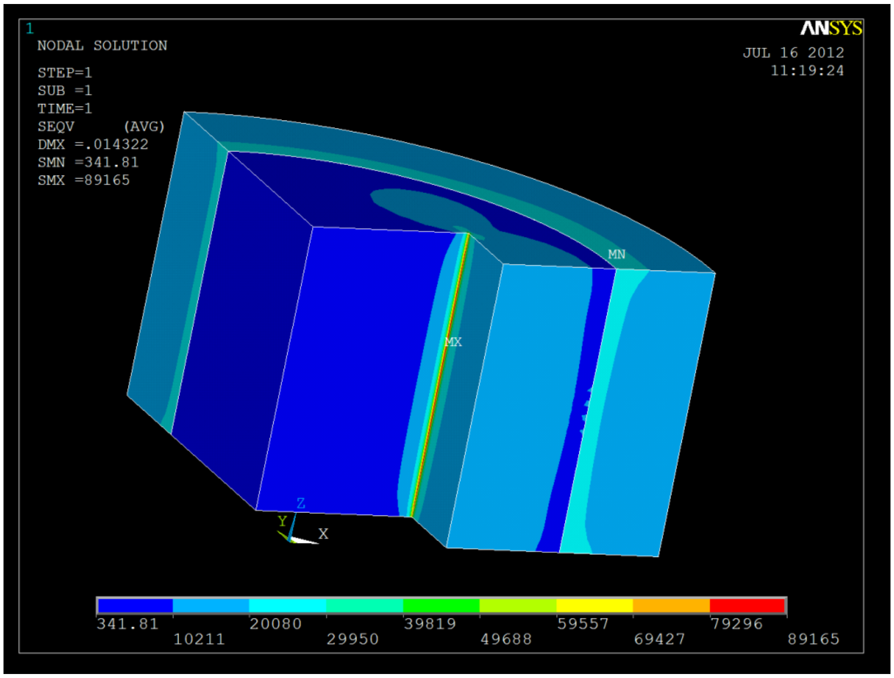

Fig. 10. Europium oxide die under no load condition—Von Mises stress.

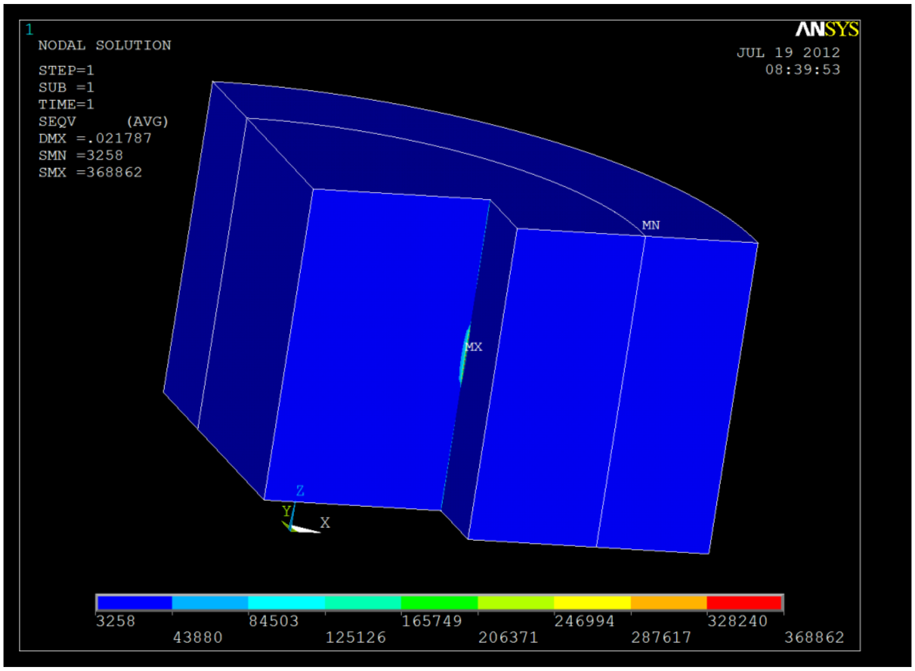

Fig. 11. Europium oxide die under loaded condition—Von Mises stress.

2.2.1 Nominal Dimensions

Analysis shows that a 0.0035 in. radius in the die corner will lead to unallowable stress levels. Therefore, the die was modeled with a 0.0055 in. radius in the corner, which led to much lower stress levels. Figures 12–15 show the die model (cut in half because of symmetrical loading) with 0.0055 in. radii in the die cavity corners and 0.0075 and 0.0080 in. diametrical interference fits between the two pieces. These models have nominal cavity dimensions of 3.4552 × 1.7246 in. The outer diameter of the outer ring is 8.150 in. and the outer diameter of the die insert is 5.960 in. As seen in Figs. 12–15, the stress levels for the nominal case are below the 312 ksi yield strength of the die insert.

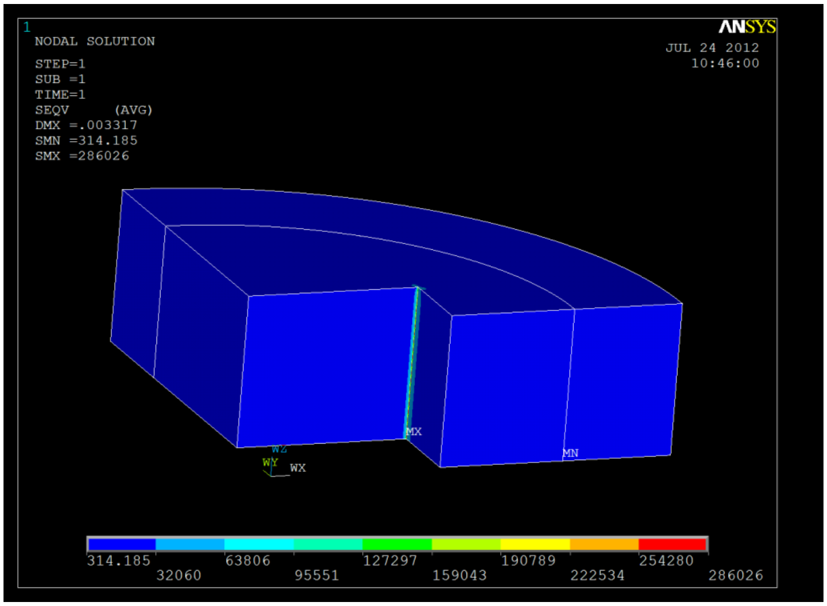

Fig. 12. Europium oxide die under no load condition—Von Mises stress, 0.0075 in. interference fit (half model).

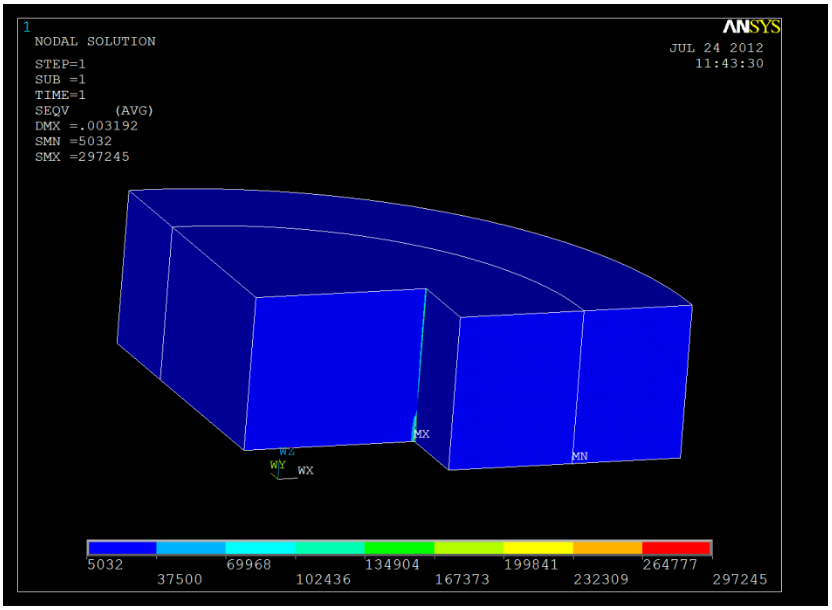

Fig. 13. Europium oxide die under loaded condition—Von Mises stress, 0.0075 in. interference fit (half model).

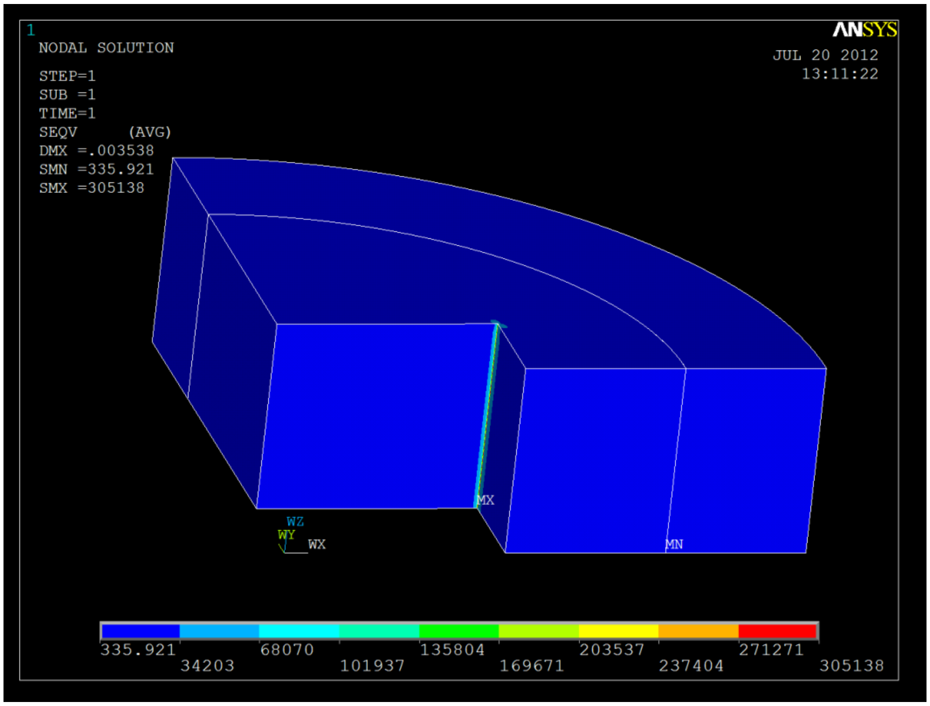

Fig. 14. Europium oxide die under no load condition—Von Mises stress, 0.0080 in. interference fit (half model).

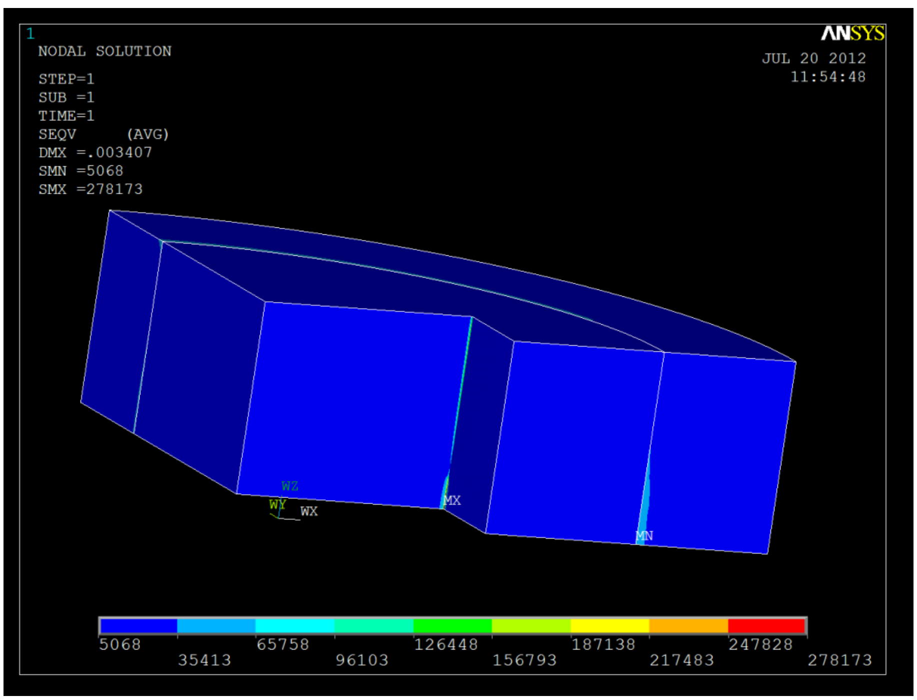

Fig. 15. Europium oxide die under loaded condition—Von Mises stress, 0.0080 in. interference fit (half model).

As seen in Figs. 12–15, the interference fit itself causes the stress in the die corner to be very close to the 312 ksi stress limit of the insert. However, when the powder compaction occurs, the force mitigates some of the stress caused by the interference fit. Therefore, the diametrical interference fit between the two parts should be between 0.0075 and 0.0080 in.

Because of the larger value of the interference fit in the europium oxide die than in the tantalum die, the displacement of the cavity walls under pressure is larger. However, the maximum cavity wall displacement is still less than 0.001 in.

2.2.2 Cavity Size

As with the tantalum die, there was the question of what would happen to the stress in the europium oxide die if the cavity size was not exactly the same as in the model. The die was therefore modeled with a slightly larger and a slightly smaller cavity size (a maximum change of 0.002 in. on each side) to determine the effect this would have on the stress in the die. As can be seen in Figs. 16 through 23, changing the cavity size by up to 0.002 in. per side does not cause the maximum stress to rise above 312 ksi in either the unloaded or loaded case. Therefore, the tolerance on the cavity wall dimensions can be ±0.002 in.

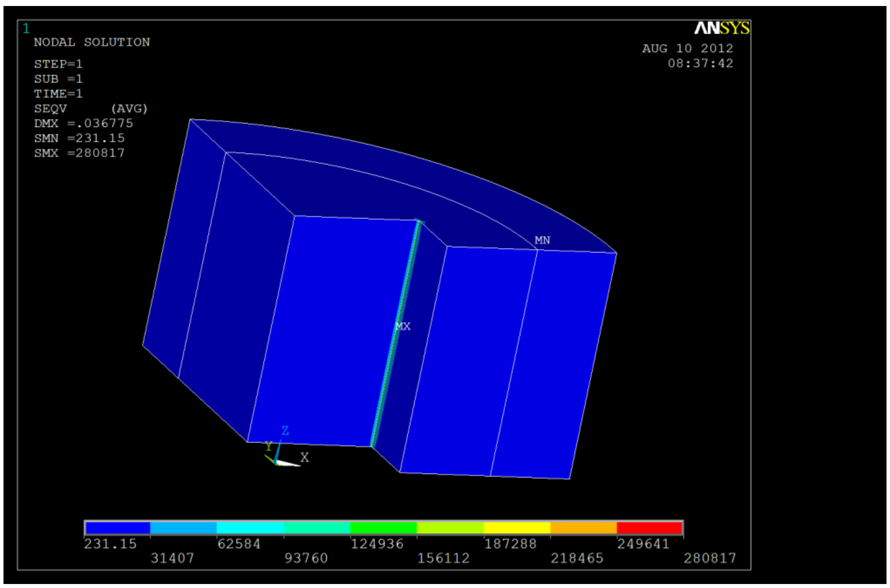

Fig. 16. Europium oxide die under no load condition—Von Mises stress, smaller cavity,0.0075 in. interference fit.

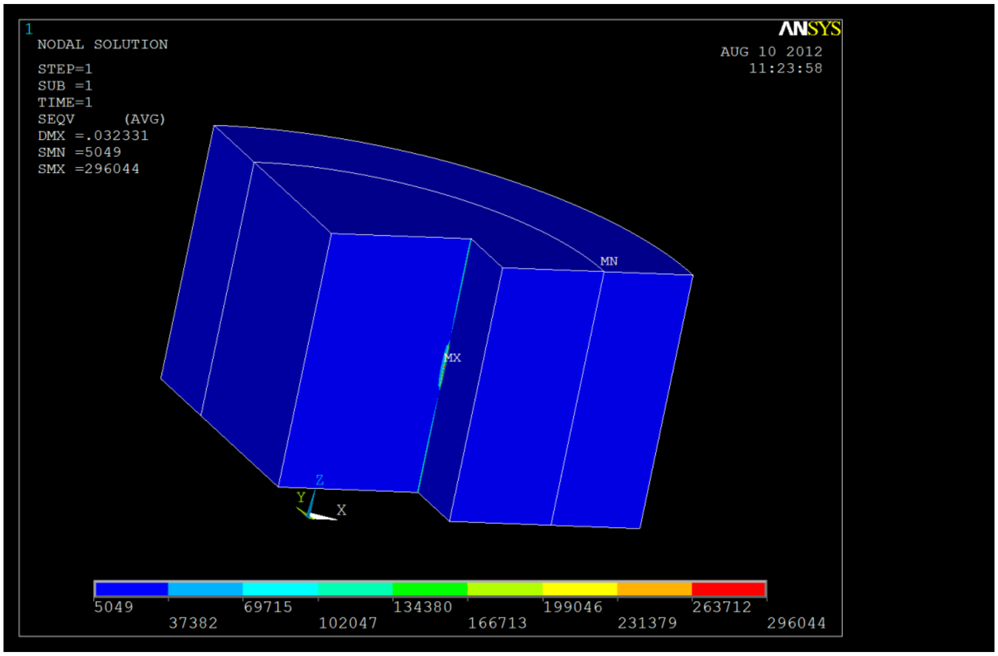

Fig. 17. Europium oxide die under symmetrical load condition—Von Mises stress, smaller cavity, 0.0075 in. interference fit.

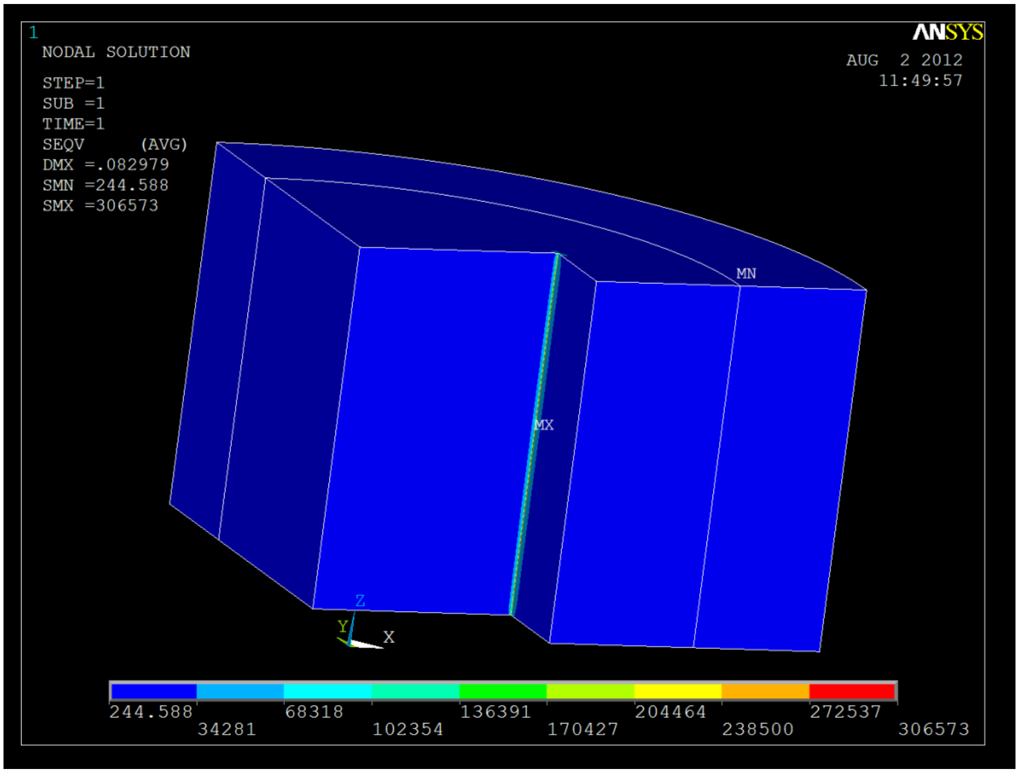

Fig. 18. Europium oxide die under no load condition—Von Mises stress, smaller cavity, 0.0080 in. interference fit.

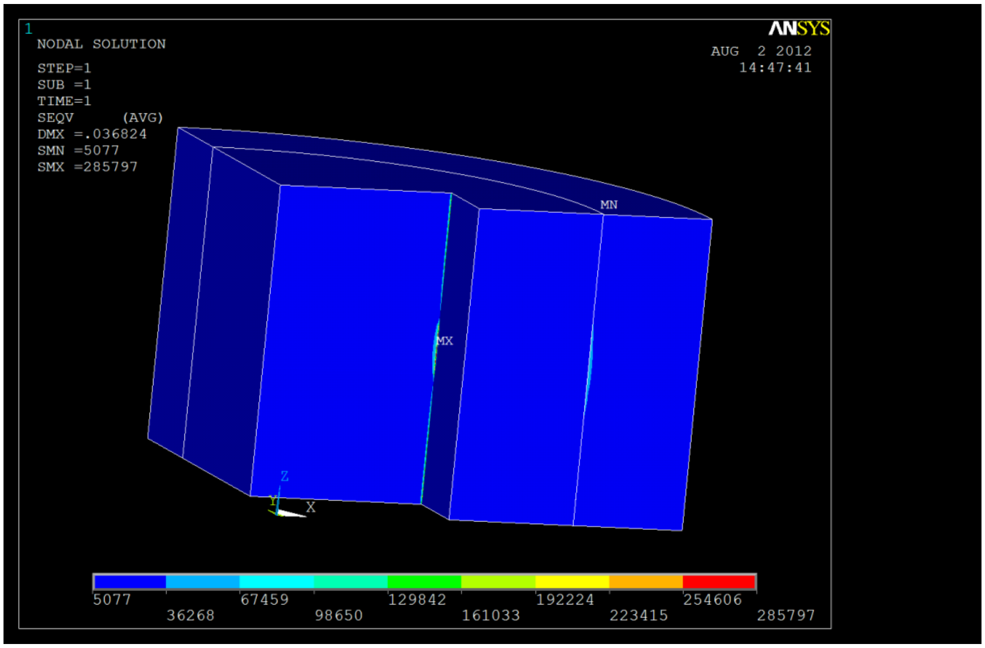

Fig. 19. Europium oxide die under symmetrical load condition—Von Mises stress, smaller cavity, 0.0080 in. interference fit.

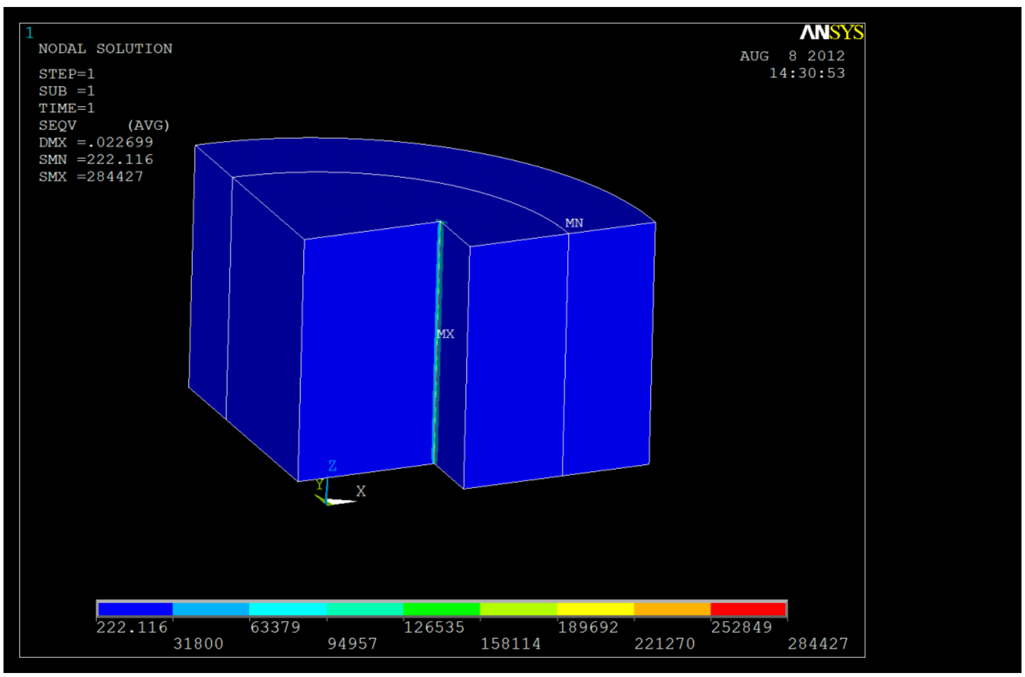

Fig. 20. Europium oxide die under no load condition—Von Mises stress, larger cavity, 0.0075 in. interference fit.

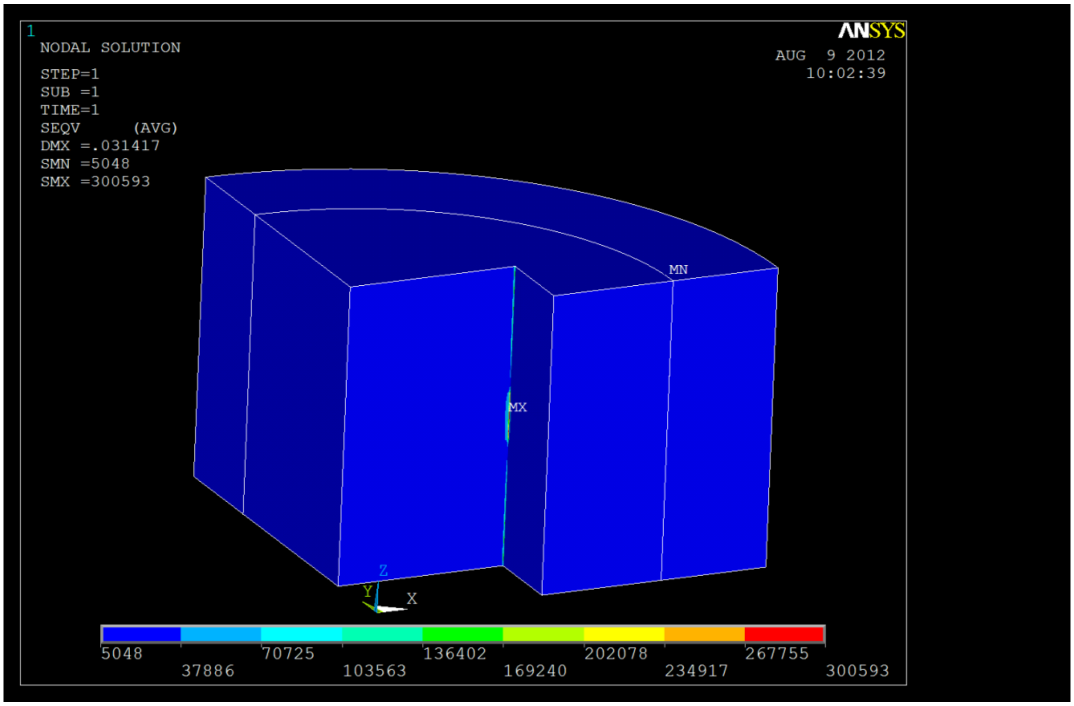

Fig. 21. Europium oxide die under symmetrical load condition —Von Mises stress, larger cavity, 0.0075 in. interference fit.

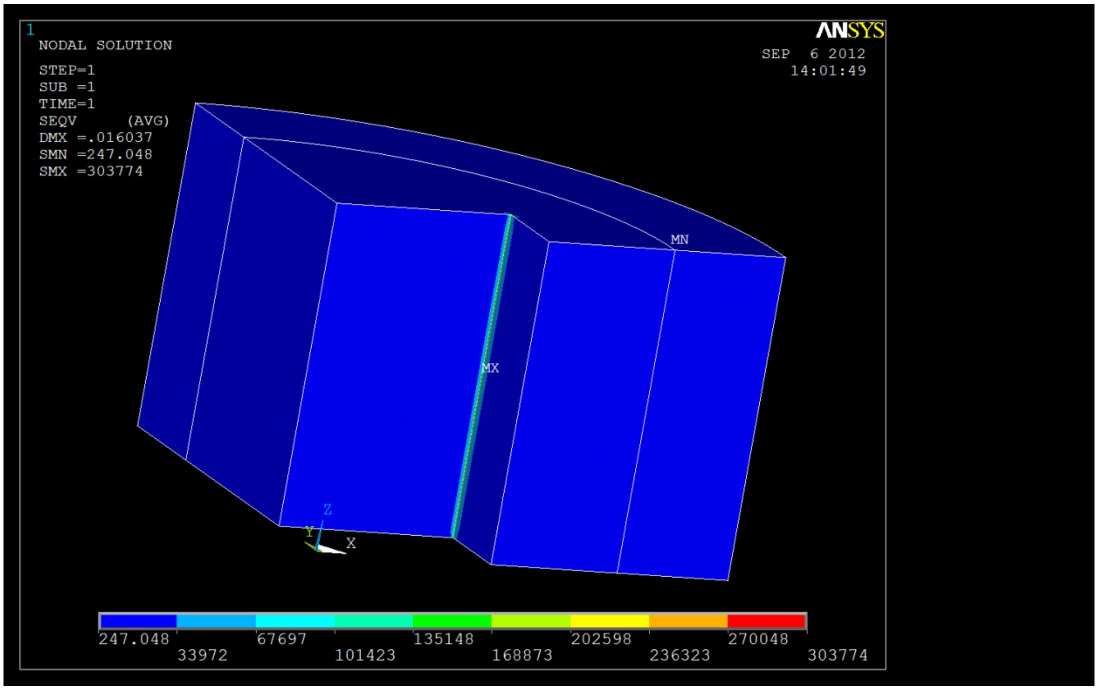

Fig. 22. Europium oxide die under no load condition—Von Mises stress, larger cavity, 0.0080 in. interference fit.

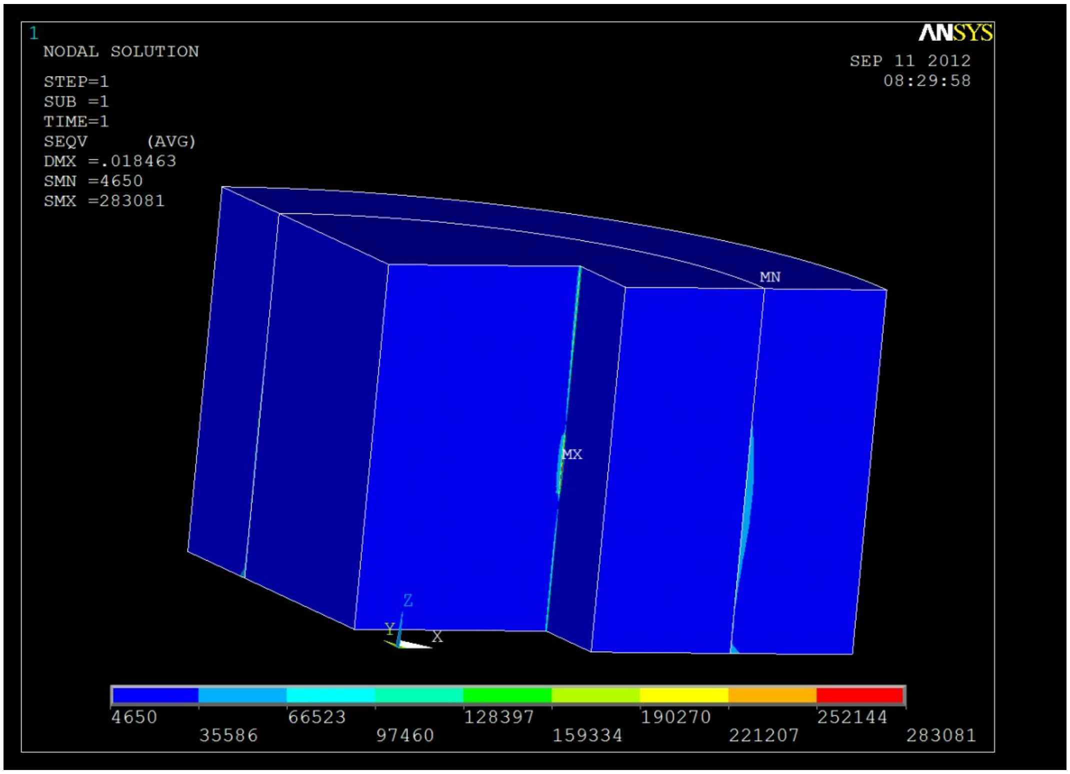

Fig. 23. Europium oxide die under symmetrical load condition— Von Mises stress, larger cavity, 0.0080 in. interference fit.

2.2.3 Asymmetrical Loading

As with the tantalum die, it was important to determine how much asymmetry could be accepted in the europium oxide die before the material would be in danger of yielding. Since this die is already much closer to the yield strength in both the loaded and unloaded case than the tantalum die, there is less margin for increasing the stress in the corners. A diagram of the loading condition is shown in Fig. 24. Figures 25 and 26 show the Von Mises stress in this loading case with both 0.0075 in. and 0.0080 in. diametrical interference fits. In this case, the stress is still below the yield strength of the material.

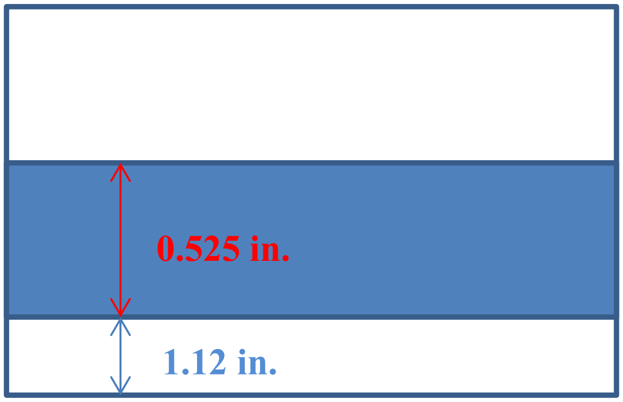

Fig. 24. Diagram showing maximum allowable asymmetrical loading (not to scale).

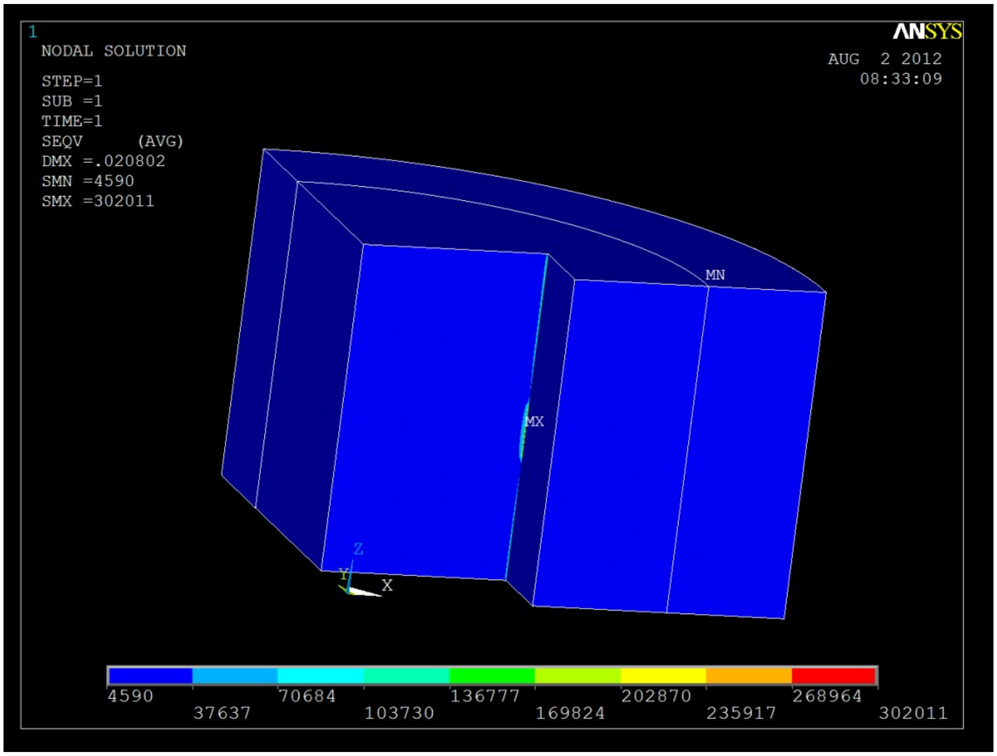

Fig. 25. Europium oxide die under asymmetric load condition—Von Mises stress, 0.0075 in. interference fit.

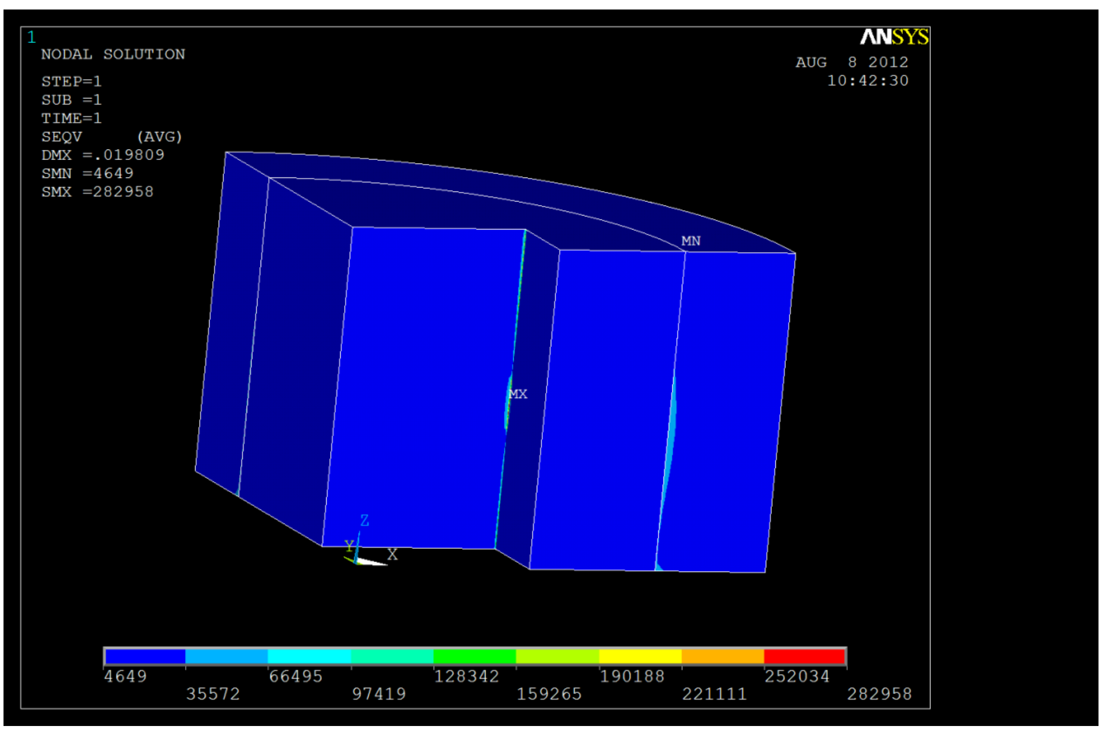

Fig. 26. Europium oxide die under asymmetric load condition—Von Mises stress, 0.0080 in. interference fit.

Figure 27 shows the asymmetrical loading case with a diametrical interference fit of 0.0075 in. where the cavity wall lengths have each decreased by 0.002 in. Figure 28 shows the same thing except that the walls lengths are 0.002 in. longer than the nominal dimensions. In both cases, the stress is below the 312 ksi yield strength limit.

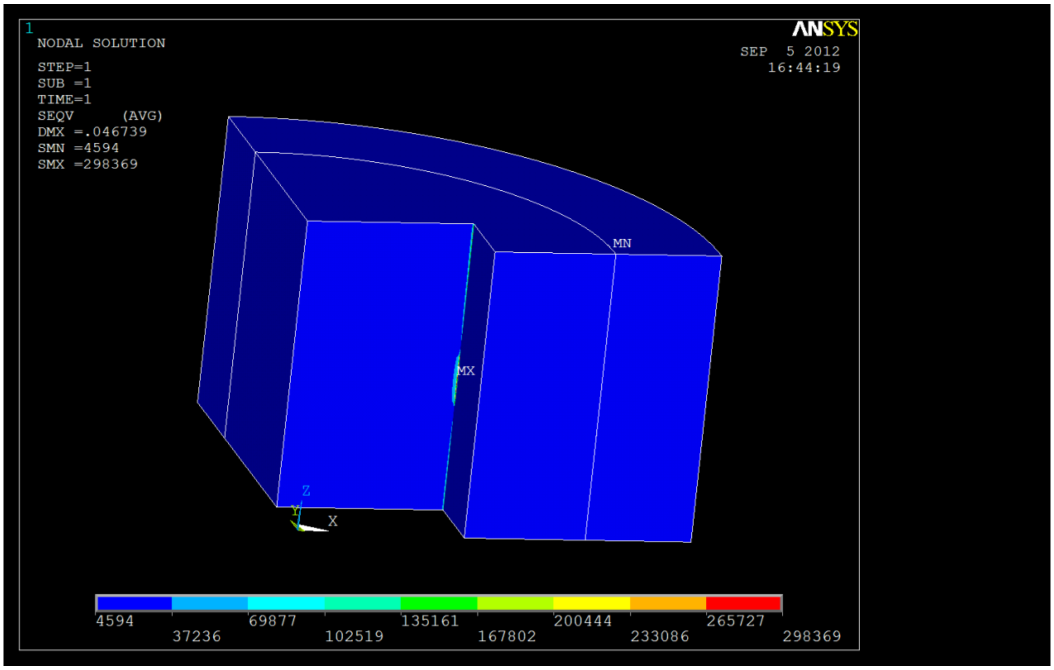

Fig. 27. Europium oxide die under asymmetric load condition—Von Mises stress, 0.0075 in. interference fit, smaller cavity.

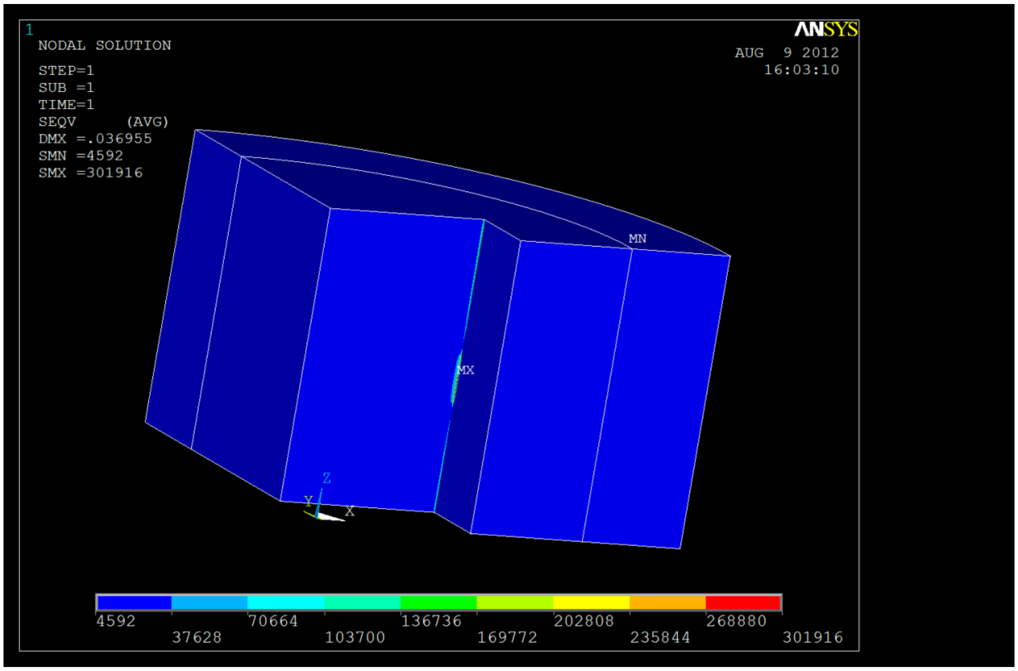

Fig. 28. Europium oxide die under asymmetric load condition—Von Mises stress, 0.0075 in. interference fit, larger cavity.

Figure 29 shows the asymmetrical load condition with a 0.008 in. diametrical interference fit where the cavity walls are 0.002 in. smaller than the nominal dimensions. Figure 30 shows the same load but with the walls 0.002 in. larger than nominal. The stress is below the yield strength of the die insert.

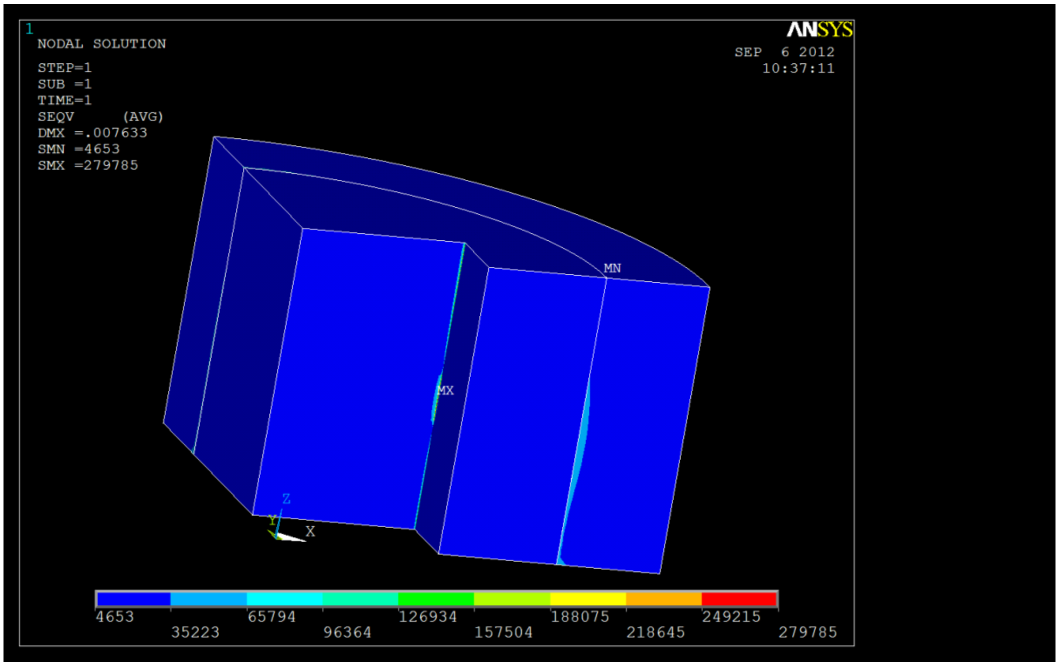

Fig. 29. Europium oxide die under asymmetric load condition—Von Mises stress, 0.008 in. interference fit, smaller cavity.

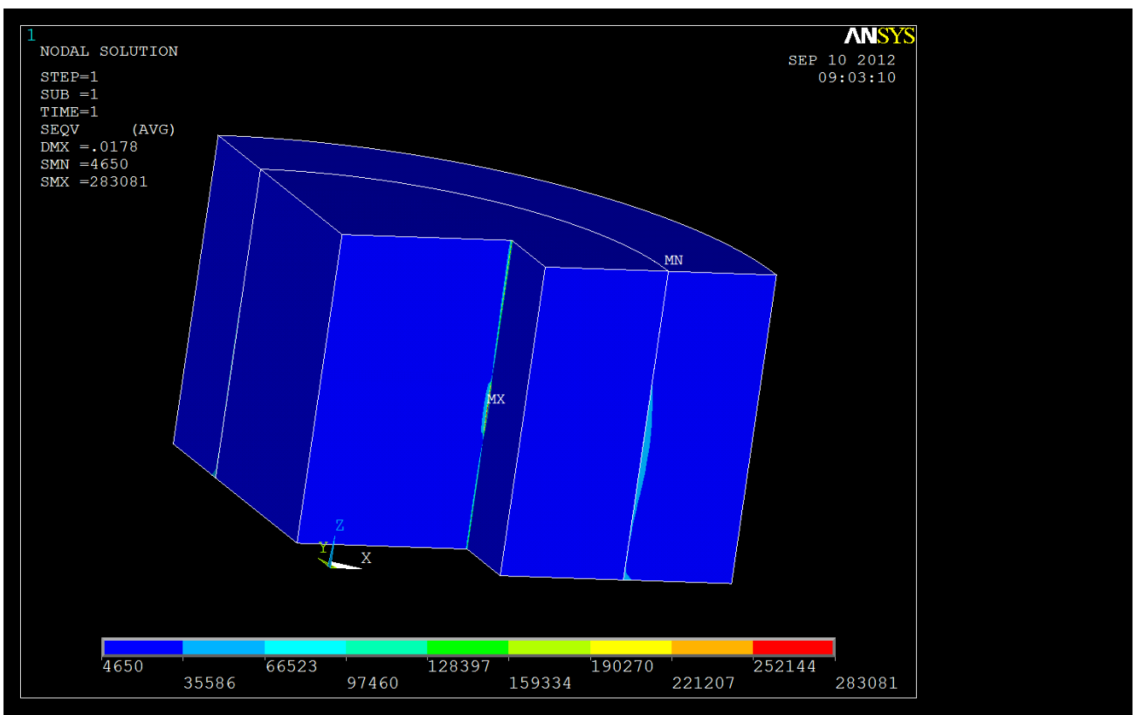

Fig. 30. Europium oxide die under asymmetric load condition—Von Mises stress, 0.008 in. interference fit, larger cavity.

Figures 27 through 30 show that the ±0.002 in. tolerance on cavity size for the europium oxide die is still acceptable with the slightly asymmetric loading described earlier. However, if the pressure is applied any farther from the center of the die, the stress in the corner is above 312 ksi. Therefore, any further load asymmetry is not recommended.

3. SUMMARY

Dies were modeled for compacting two types of powder into metal compacts: tantalum and europium oxide. For the tantalum die, a diametrical interference fit of 0.0020 in. between the outer ring and the insert is acceptable, and the inner corner radius can be as small as 0.0035 in. The insert has an outer diameter of 6.150 in. The cavity in the insert is 3.4640 × 0.8086 ± 0.002 in. and the outer ring has an outer diameter of 8.150 in. The die is 2.960 in. deep. With these design parameters, the plate can be formed so that its edge is 0.500 in. from the top or the bottom of the die.

For the europium oxide die, the diametrical interference fit between the outer ring and the insert must be between 0.0075 and 0.0080 in. The inner corner radius can be as small as 0.0055 in. The insert has an outer diameter of 5.960 in. The cavity in the insert is 3.4552 × 1.7246 ± 0.002 in. and the outer ring has an outer diameter of 8.150 in. The die is 3.020 in. deep. With these design parameters, the plate can be formed so that its edge is 1.225 in. from the top or the bottom of the die.

4. REFERENCES

1. Coffey, Ethan, *Two-Piece Compaction Die Design*, ORNL/TM-2010/48, Oak Ridge National Laboratory, March 2010.

2. ANSYS Mechanical, Version 12.1, ANSYS, Inc., Canonsburg, Pennsylvania, January 2009.

5. INTERNAL DISTRIBUTION

1. Ethan Coffey
2. Brian Damiano
3. Daniel Pinkston
4. Charles Schaich
5. ORNL Office of Technical Information and Classification