28.0 LABORATORY TESTING TO IDENTIFY PERMANENT PVD COATINGS TO MINIMIZE LUBRICANT USE DURING FORGING

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28.1 Project Overview and Industrial Relevance

The Colorado School of Mines (CSM) Metallurgical and Materials Engineering Department puts an emphasis on supplying relevant knowledge related to industrial operations, materials processing, property application and selection. One of the many goals of the CSM Center for Advanced Non-Ferrous Structural Alloys (CANSFA) is to further understand how process alteration affects the overall performance of a material. One of these industries where process affects material properties and performance is the forging industry.

CANSFA is working to identify how a different coating on open faced dies affects the friction associated with forging operations for given materials. These coatings will be placed on open dies using physical vapor deposition (PVD), and other techniques. In order to test different coatings, a modified open die system will be required where multiple replaceable faces/surfaces for the dies with different and unique PVD coatings on each face can be tested.

28.2 Background

Forging dies have been manufactured and used at CSM for many years to, among other things, perform ring tests [28.1-28.3] to determine friction during forging operations. These dies are used on a 100 kip MTS hydraulic mechanical testing frame, equipped with displacement and load sensors. The current dies, pictured in **Fig. 28.1a** assembled on the hydraulic press, and in **Figs. 28.1b** and **1c** individually, are both 6 inches in diameter and 2 inches in height. **Fig. 28.1a** shows a lubricated aluminum ring ready to be tested. **Fig. 28.1c** shows two protrusions on either side of the top die with a wire wrapped around both of them, which is how the top die is attached to the hydraulic press. Once the hydraulic press is lowered far enough, an upward normal force from the workpiece between the top and bottom die secures the top die in place preventing its movement. The bottom die, **Fig. 28.1b**, is situated below the top die and has three threaded holes evenly spaced to hold it in place on the ram of the hydraulic press. The design aspects that will transfer from the current dies to the new dies are the overall outer dimensions.

The new dies will have a diameter of 6 inches and remain 2 inches tall. The modified die design described here incorporates replaceable inserts to enable ring-test friction evaluations using a wide variety of die coatings. **Fig. 28.2** shows example aluminum rings after testing to various levels of deformation (increasing from left to right), and with different lubricants (top to bottom), where friction conditions can be quantified simply by measuring the inside diameter (ID) and outside diameter (OD) of the rings after testing. Higher levels of friction result in a reduction of the ID, whereas low friction conditions result in increases in both the ID and OD. The design goals for the new dies are to (1) allow for interchangeable inserts with different coatings to be easily switched in and out of the die bases, (2) allow the tests to be executed with these new dies and be operable by a single individual, (3) enable the tests to be run at elevated temperatures up to 500˚C, (4) produce dies, and particularly inserts, that minimize the amount of machining required for production, and (5) ensure that valid ring-test friction evaluations can be made.

A challenge associated with the new dies is creating a simple design that will satisfactorily meet the requirements of this project. A simple design will decrease the cost associated with machining, facilitate operation by the user, and eliminate the need for multiple people to be required when testing is performed. Since the dies and their replaceable faces will be tested at elevated temperatures, thermal expansion of material is another challenge that needs to be taken into consideration. The altered top die poses some challenges due to the fact that both the die and the replaceable face need to be suspended and secured against the hydraulic press. One potential solution to this problem would be to use pins to lock the die into place but those pins would undergo large shear stresses with a perfect fit as well as potentially coming loose during the setup of a test.

Both dies and especially their replaceable faces need to be resistant to corrosion and designed to consider thermal expansion, creating the necessity for a suitable material to be chosen and heat-treated appropriately.

28.3 Results

28.3.1 Top Die

Fig. 28.3 illustrates the design of the top die that will be attached to the hydraulic press. The ¼ inch screws protruding from the side will be wrapped with wire which are then wrapped around bolts protruding from the hydraulic press. This will hold the die against the press until the normal force created during the tests securely fixes the top die against press. The cylindrical cutout of the die will house the replaceable insert for the die. The slanted cut around the bottom of the cylindrical cutout will work in coordination with a complementary cutout on the insert to allow for an intimate mating between the insert and the holder surfaces. The flat cuts on the outer circumferences of the die will host the pin hole and an additional screw hole which will be used to hold a piece of material over the end of the pin holding it securely in the indent on the top insert.

28.3.2 Bottom Die

Fig. 28.4 shows the design of the bottom die. The bottom die requires less complexity than the top die. It does not need to be held up against the force of gravity. Because of this, three threaded holes evenly spaced 120˚ apart will be utilized to hold the die in place on the bottom plate of the hydraulic press. Much like the top die, there is a slanted cut made on the bottom of the cylindrical cutout that will allow for an intimate mating between the bottom insert and the surface of bottom holder. The three holes on the outside of die that go through the entire surface are there in the case that an insert becomes cold welded to the inside of it. These holes will allow removal of the inserts in the event of sticking.

28.3.3 Top Insert

Fig. 28.5 illustrates the top insert. The top insert has an indented and smooth circular cut around the middle section of it that will allow for an easy insertion of the pin into the indentation. The cut is around the entire circumference of the insert. As discussed previously, the pin will be held in by a piece of material on the end pin which will be held against the indentation. The purpose of this indentation is to facilitate fast interchange of inserts for tests occurring at high temperatures. This will eliminate excessive temperature loss to the surroundings while placing and securing the heated inserts. Finding a specific hole on the insert with a pin would mean longer handling of hot metal pieces which is minimized with the indented cut. The slanted cut on the bottom side of the die that lies inside the holder is to identify which side of the die has the PVD coating on it. By not having two identical sides it is easier to figure out which side of the insert has the coating. The circumference of the inserts is smaller than the circumference of the cylindrical cut made in the holders of the inserts to account for the thermal expansion that will occur when testing at elevated temperatures. The three holes on the outside of die are there for the same reason as the bottom die’s three holes: to allow removal of an insert in the case it sticks to the inside of the die.

28.3.4 Bottom Insert

Fig. 28.6 illustrates the bottom insert. The bottom counterpart to the top is once again simpler in design. The bottom insert has no indentation around the circumference for a pin to be inserted into it. The bottom insert will sit in the cylindrical cutout of the bottom die. It is similar to the top die in that it has the slanted cut to allow for easy identification of which side has the PVD coating on it. Because the dies will be made out of ferrous material the removal and changing of the bottom inserts can occur with a magnet. The bottom inserts are designed similar to the top inserts in that the circumference is smaller than the circumference of the cylindrical cut made in the holder to account for thermal expansion.

28.3.5 Pins

Fig. 28.7 shows the pin that will be used in conjunction with the spring to hold the top insert in place. The pin will have a rounded end that fits into the indentation of the insert. The pin is long enough to penetrate the entire die while having enough room left over to pull it out and release the insert. The pin is not a perfect fit to the indentation in order to eliminate as much shear stress as possible.

28.3.6 Material

A variety of material will be used to construct this replaceable insert system. For the pieces that serve as the holders of the replaceable inserts, 4140 steel will be used. The inserts will be superior grade H13 steel. H13 steel is resistant to thermal fatigue cracking that occurs from repeated heating and cooling cycles. The processing and treatment of the inserts will take place as follows:

- Rough machining
- Heat treat to/close to 50 HRC
- Finish machining
- Polish surface to approximately 1 micron
- Nitride
- PVD coating

28.3.7 Modeling

In order to visualize the stress and distribution of stress that will be on the die inserts during testing, the modeling software DEFORM® was used. A model of the inserts was put into DEFORM®, with an aluminum ring between them, at room temperature with a 0.2 inches per second compression velocity applied to a 100 kip force. The highest effective stress shown in the model was 32.8 ksi which is slightly less than the mathematical calculations using the equation below.

$$\sigma = \frac{F}{A}$$

The calculated stress for an aluminum ring of outer diameter of 1 in. and inner diameter of 0.5 in. was 33.9 ksi. This difference between the calculated and modeled stress is negligible because the yield strength of H-13 listed from Bohler-Uddeholm is 185 ksi at 45 HRC and 220 ksi at 52 HRC. Since the yield strength is higher than the effective stress of the tests there will be no plastic deformation at the surface of the inserts. The distribution of stress on the surface of the inserts can be seen in **Fig. 28.8**.

28.3.8 Manufacturing

The dies are currently being machined and heat treated at Golden Machining Solutions, Golden, CO, with an anticipated completion date of May 1, 2018. One top and one bottom die are being machined, along with six sets of the top and bottom inserts. One each of the top and bottom die inserts will be made from H-13 steel and W303 Isodisc (1.2367) alloy steel, both supplied by Bohler-Uddeholm. The remaining H-13 inserts will be made from H-13 steel supplied Hitachi. Upon completion of the dies, initial trials will be performed on uncoated die inserts to develop procedures for room temperature and high-temperature ring tests. During these trials, the remaining inserts will be sent for coating application.

28.4 Conclusions

A fully assembled model of the replaceable insert die system can be seen in **Fig. 28.9**. The goal of this project is to perform research on the effect of various PVD coatings on friction during forging operations, to determine if reduced levels of conventional lubricants can be used in commercial forging operations. This design's purpose is to allow for an efficient way of testing these different PVD coatings. Moving forward, obtaining the materials and machining will take place.

28.5 References

28.1 Male A.T. and Cockcroft M.G. "A method for the determination of the coefficient of friction of metals under condition of bulk plastic deformation.", J. Inst. Metals 1964–1965, 93, 38–46.

28.2 Avitzur B. *Metal forming: processes and analysis.* New York: McGraw Hill, 1968.

28.3 Sofuoglu H., Rasty J. "On the measurement of friction coefficient utilizing the ring compression test", Tribology Intl., 1999, 32, 327-335.

(a)

(b)

(c)

Figure 28.1: (a) Forging dies assembled on the 100 kip hydraulic load frame at Colorado School of Mines, showing a lubricated aluminum ring ready for testing. Ring tests are performed on the flat sides of the dies. The bottom die rests on a compression platen on the hydraulic ram, and the top die hangs from a compression platen with a spherical seat that is attached to a load cell and the press crosshead. (b) The bottom die is reversible, with a "CSM" imprint on one side and a flat face on the opposite side. The guides keep the die from sliding off the bottom ram of the hydraulic press. (c) The top die is also reversible, with an impression on one side and a flat face on the opposite side. This die hangs from the upper tooling on the hydraulic press via the pictured wires. Dies are 6 inches in diameter.

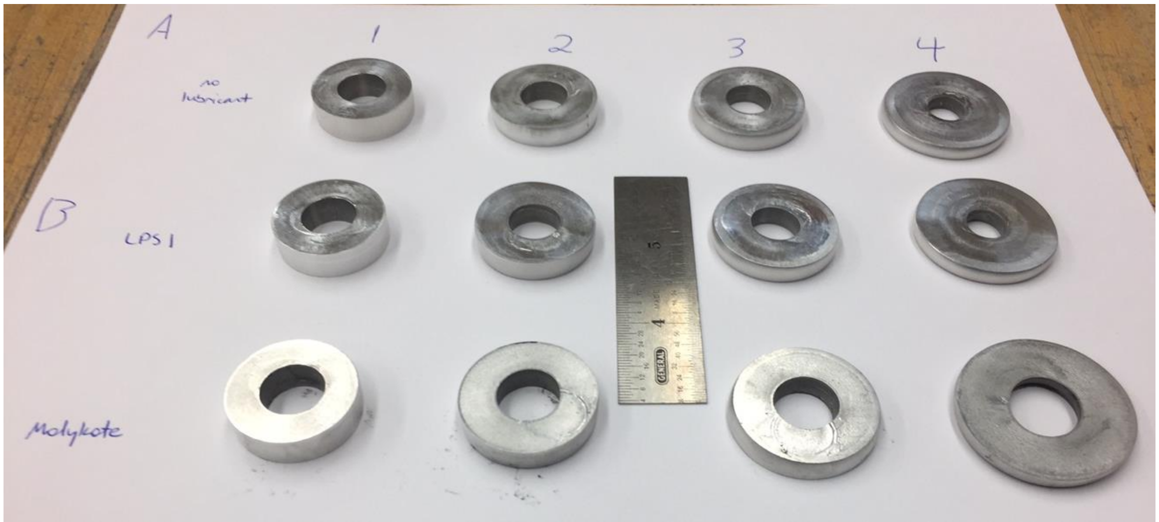

Figure 28.2: Example aluminum rings that have been tested to various levels of deformation (increasing from left to right) and using various lubricants (top to bottom) show the relative friction coefficient for the various lubricants on flat steel forging dies.

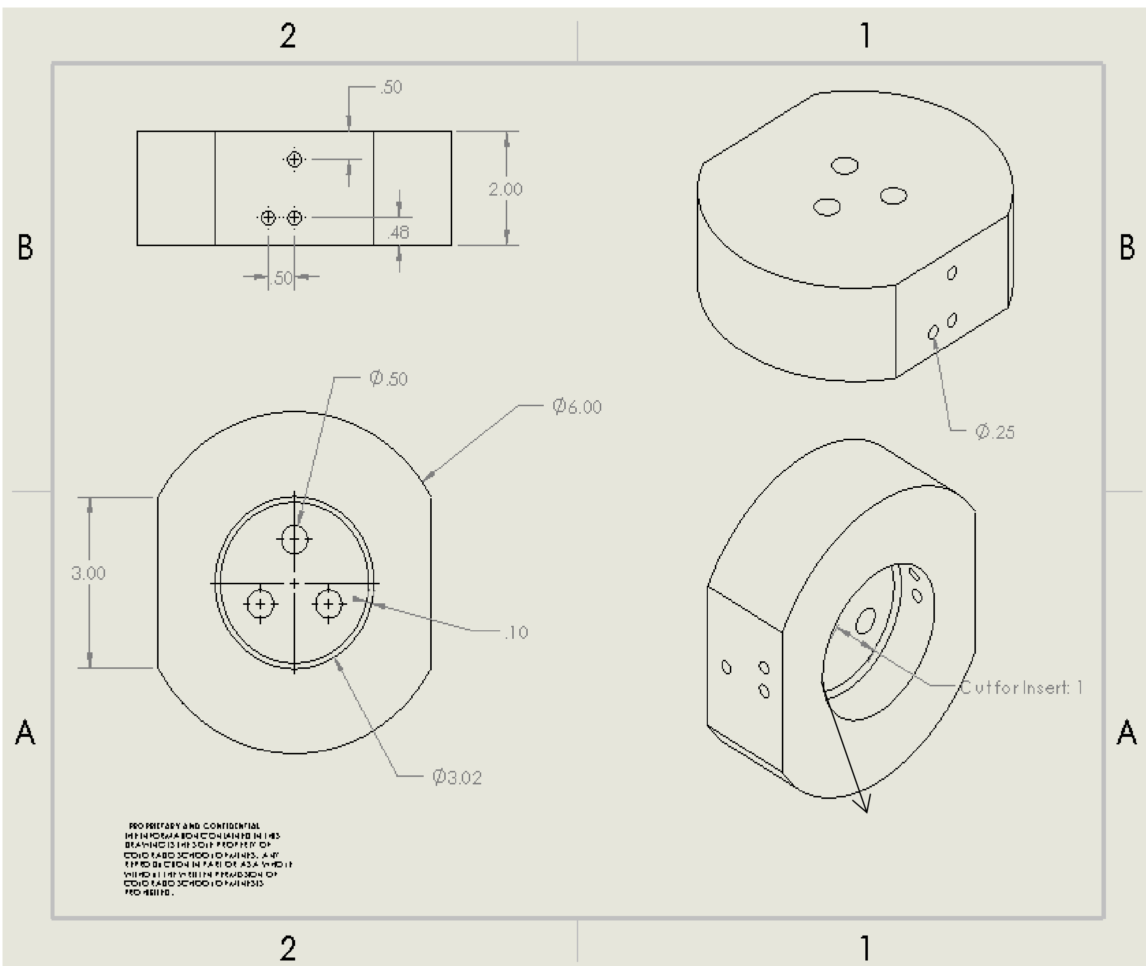

Figure 28.3: Engineering drawing of the base of the top die, showing the cavity that will hold the coated insert (see Fig. 28.5). Dimensions in inches.

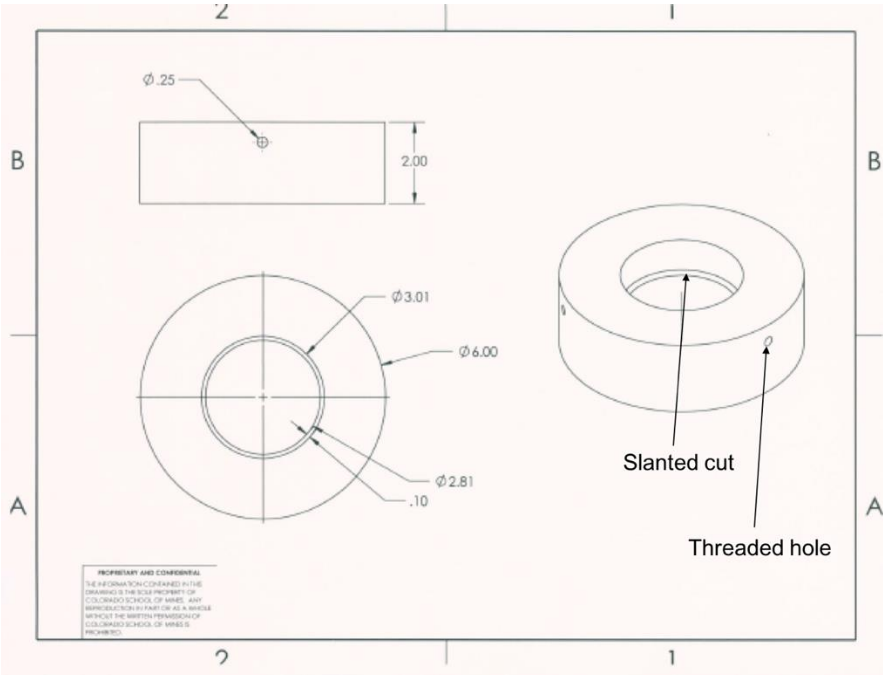

Figure 28.4: Engineering drawing of the base of the bottom die, showing the cavity that will hold the coated insert (see Fig. 28.6). Dimensions in inches.

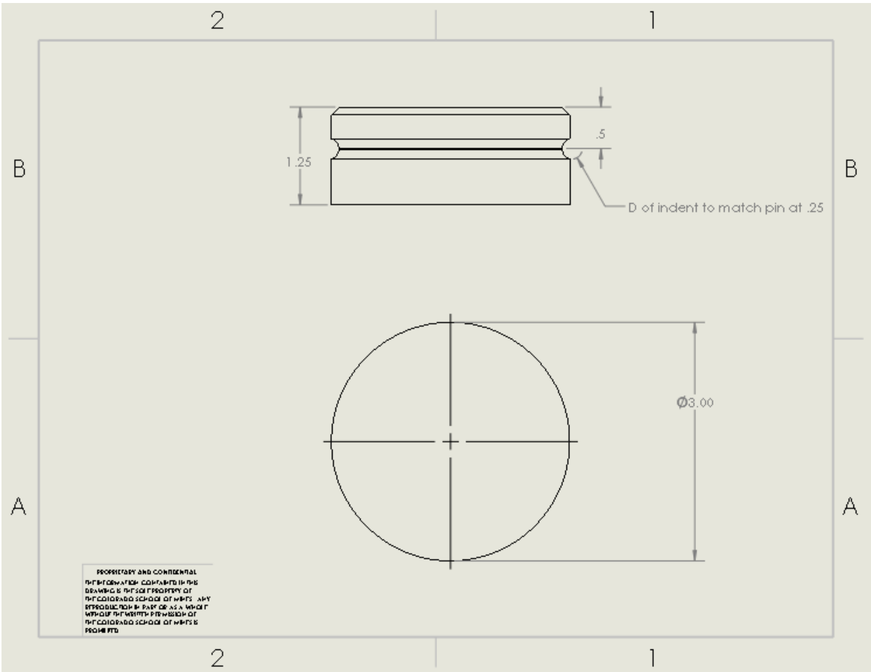

Figure 28.5: Engineering drawing for the replaceable insert for the top die, showing the indentation for the retaining pin, along with the slanted cut to ensure seating into top die base (Fig. 28.3). Dimensions in inches.

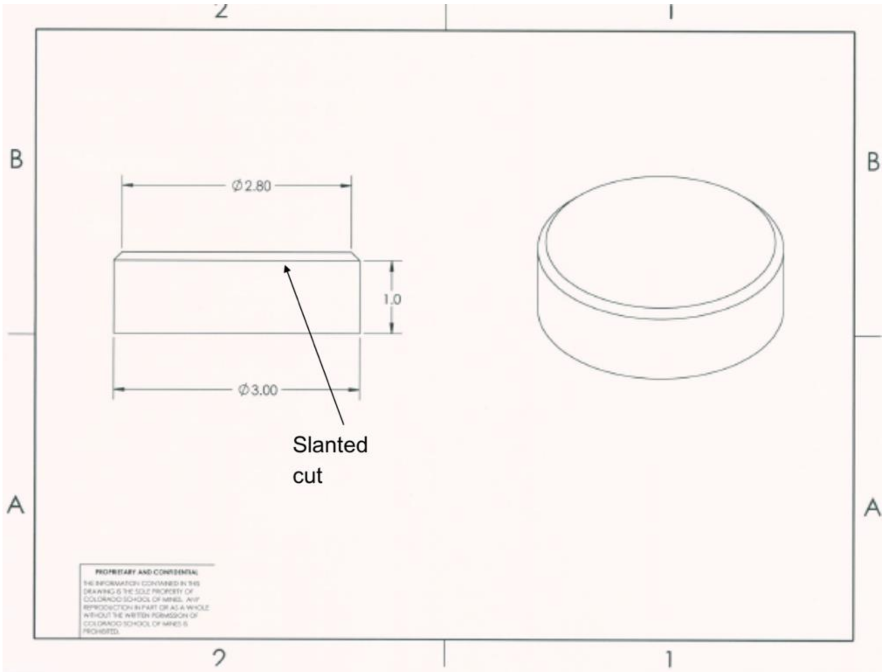

Figure 28.6: Engineering drawing for the replaceable insert for the bottom die, showing the slanted cut to ensure seating into the bottom die base (Fig. 28.4). Dimensions in inches.

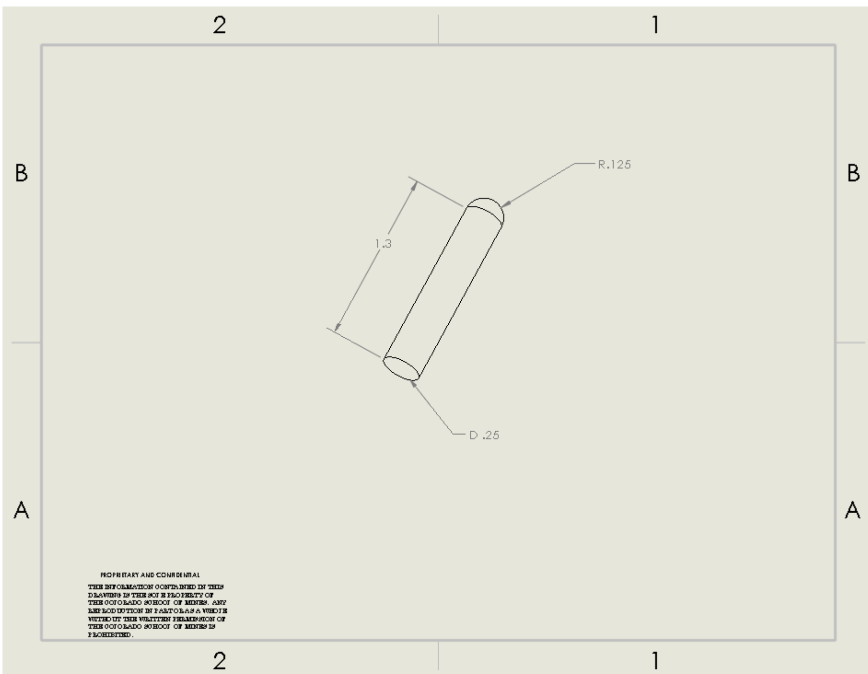

Figure 28.7: Engineering drawing for pin used to hold the top insert (Fig. 28.5) in the top die (Fig. 28.3). Dimensions in inches.

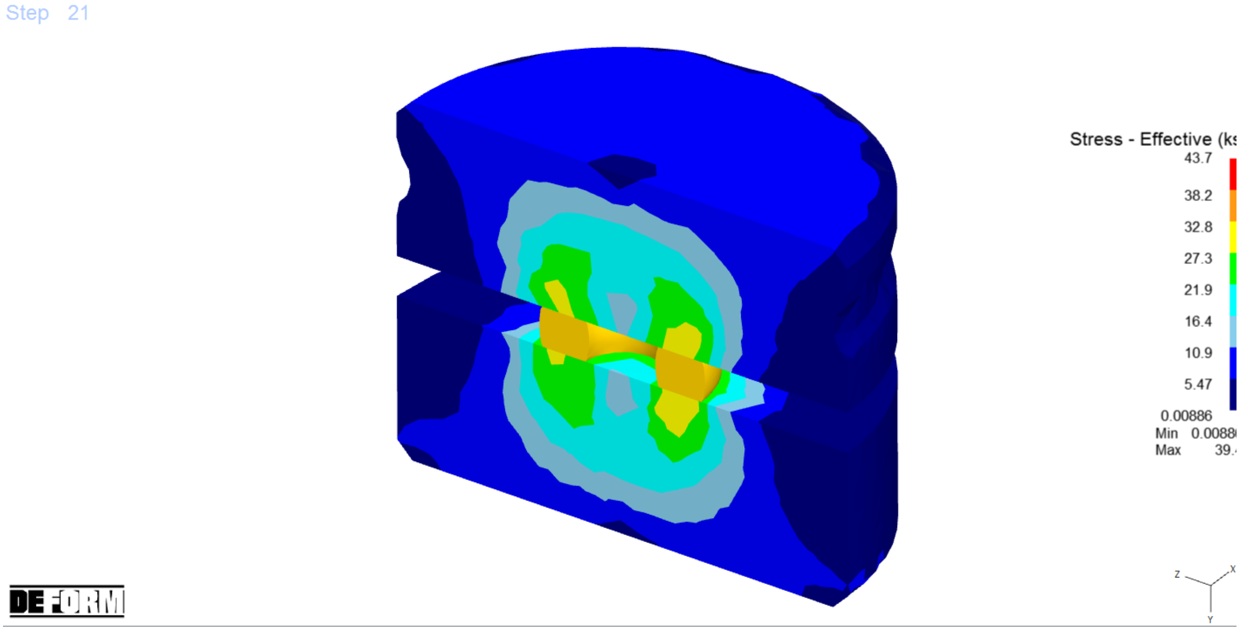

Figure 28.8: A cross-section view of the room temperature DEFORM model. Pictured with aluminum ring between top and bottom inserts.

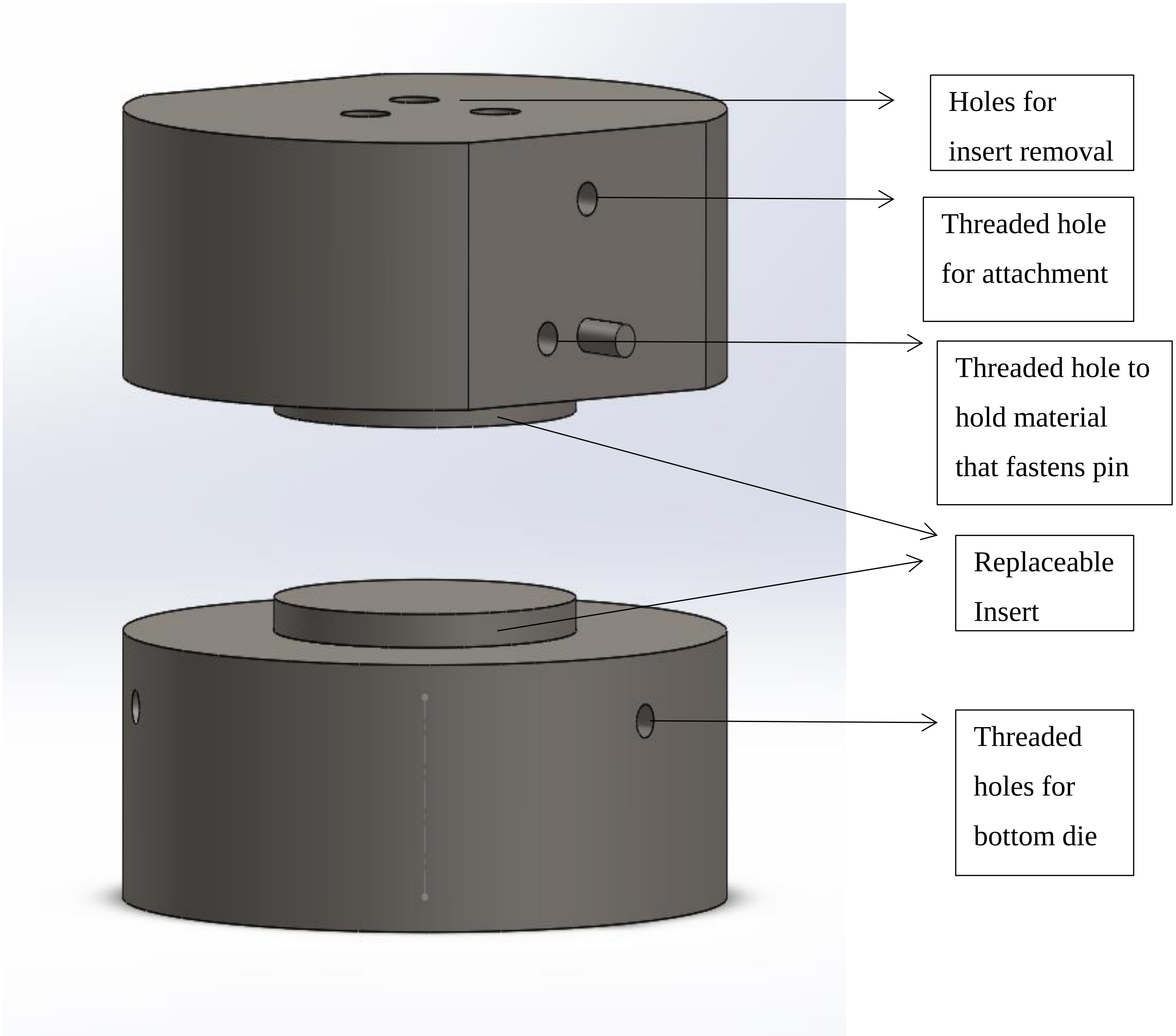

Figure 28.9: Schematic view of the die assembly, including top and bottom dies and showing die insert in the bottom die.