Appendix A

Component Drawings

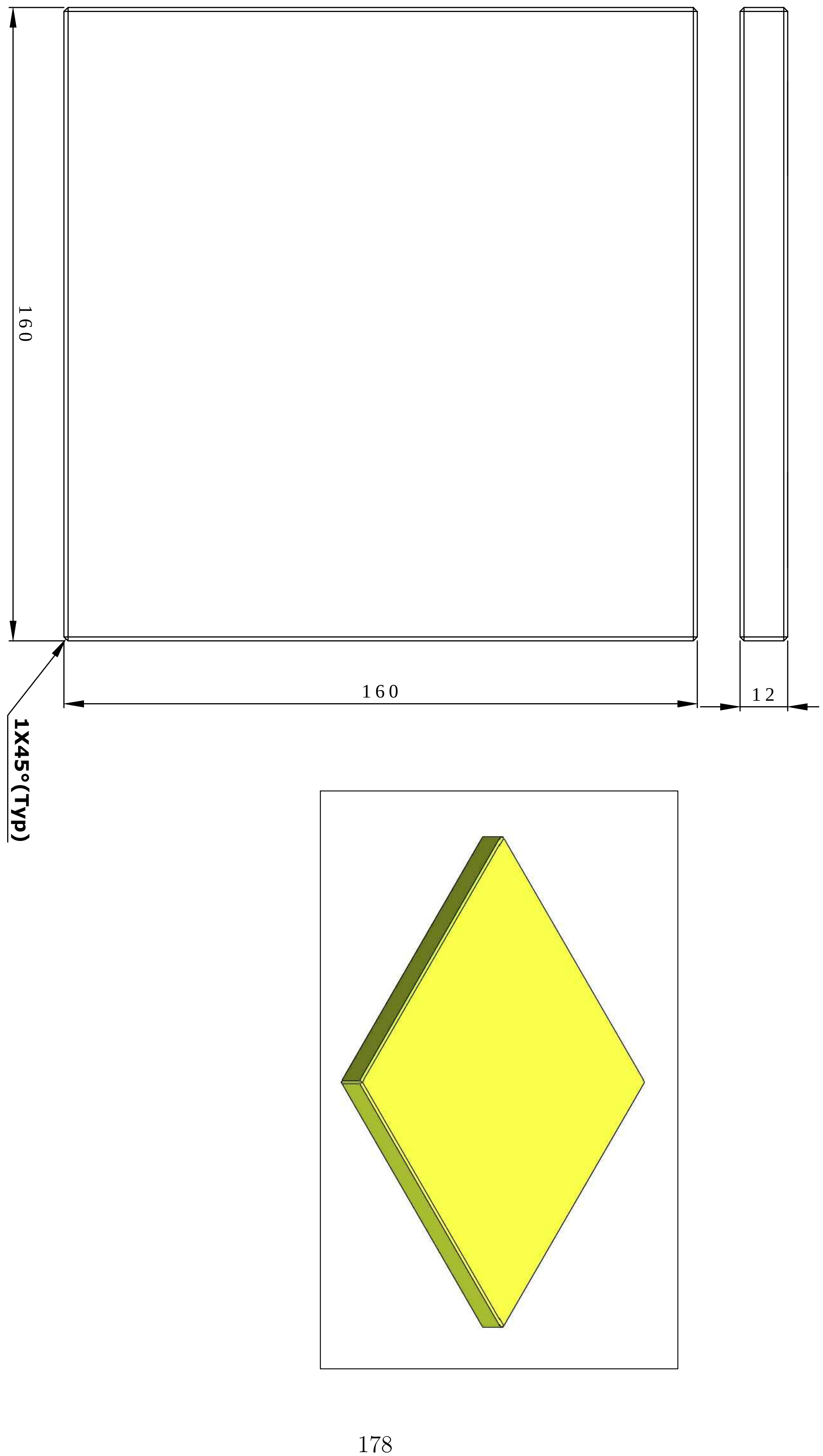


Figure A.1: Base Plate

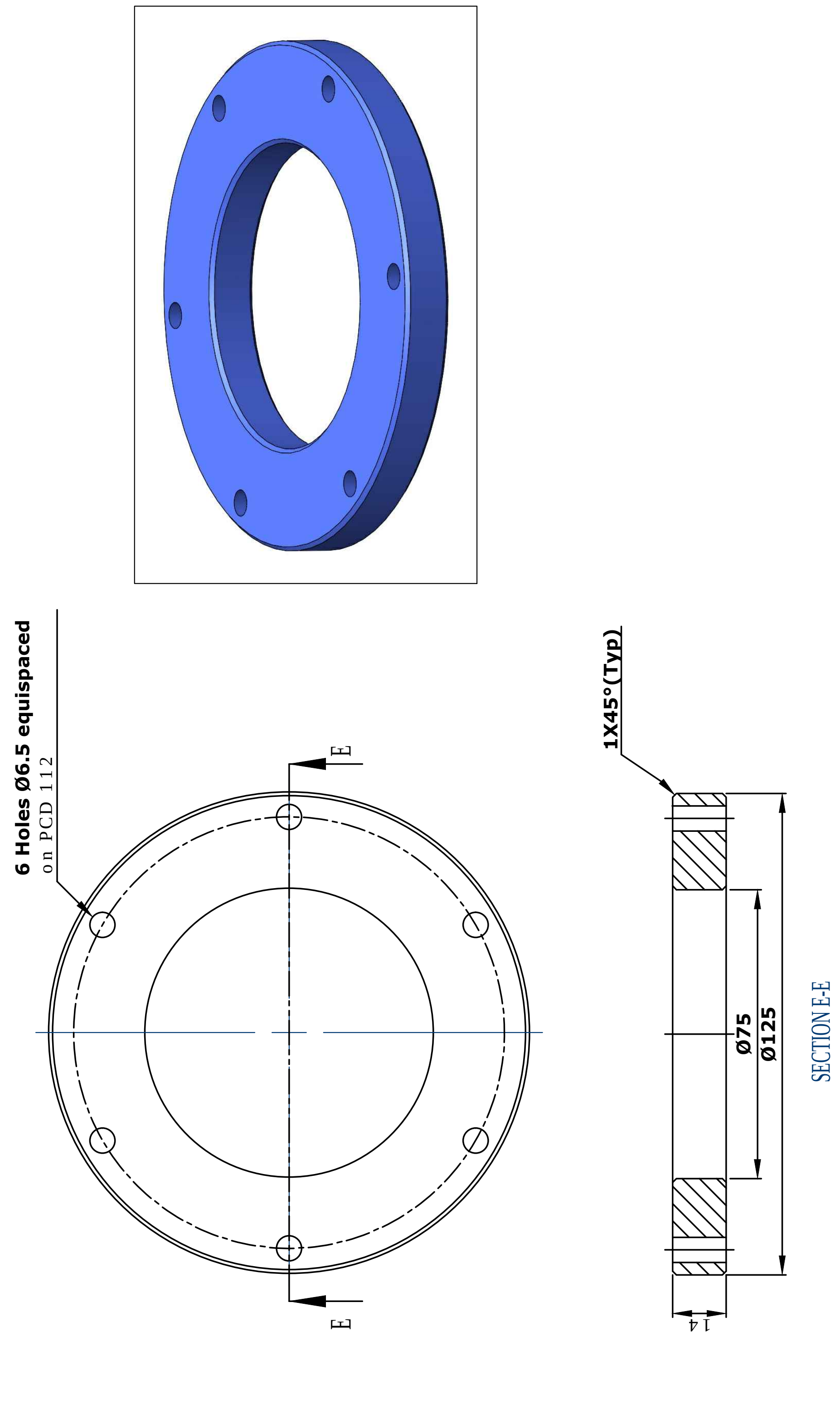


Figure A.2: Blank Holder

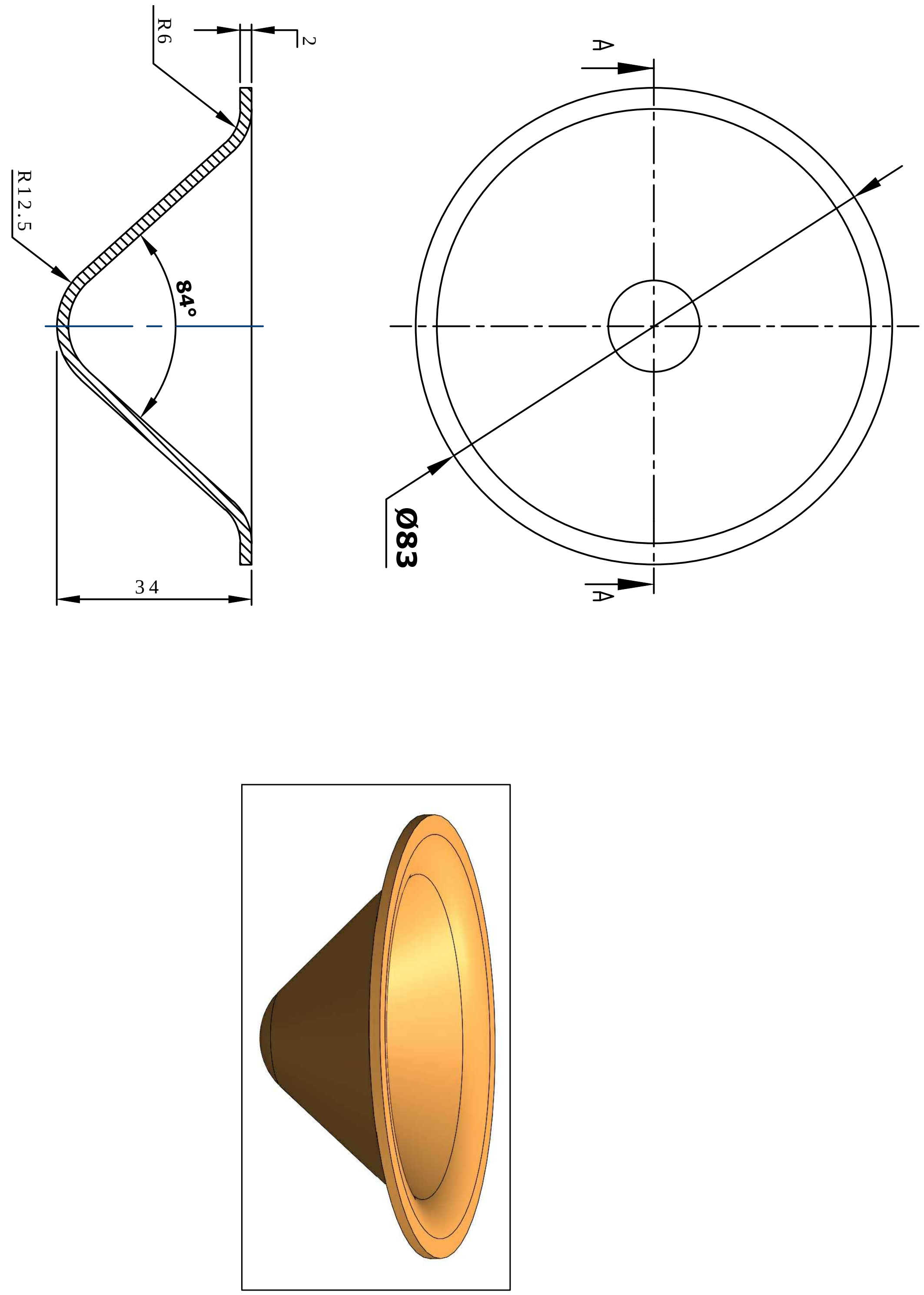


Figure A.3: Cone (84°)

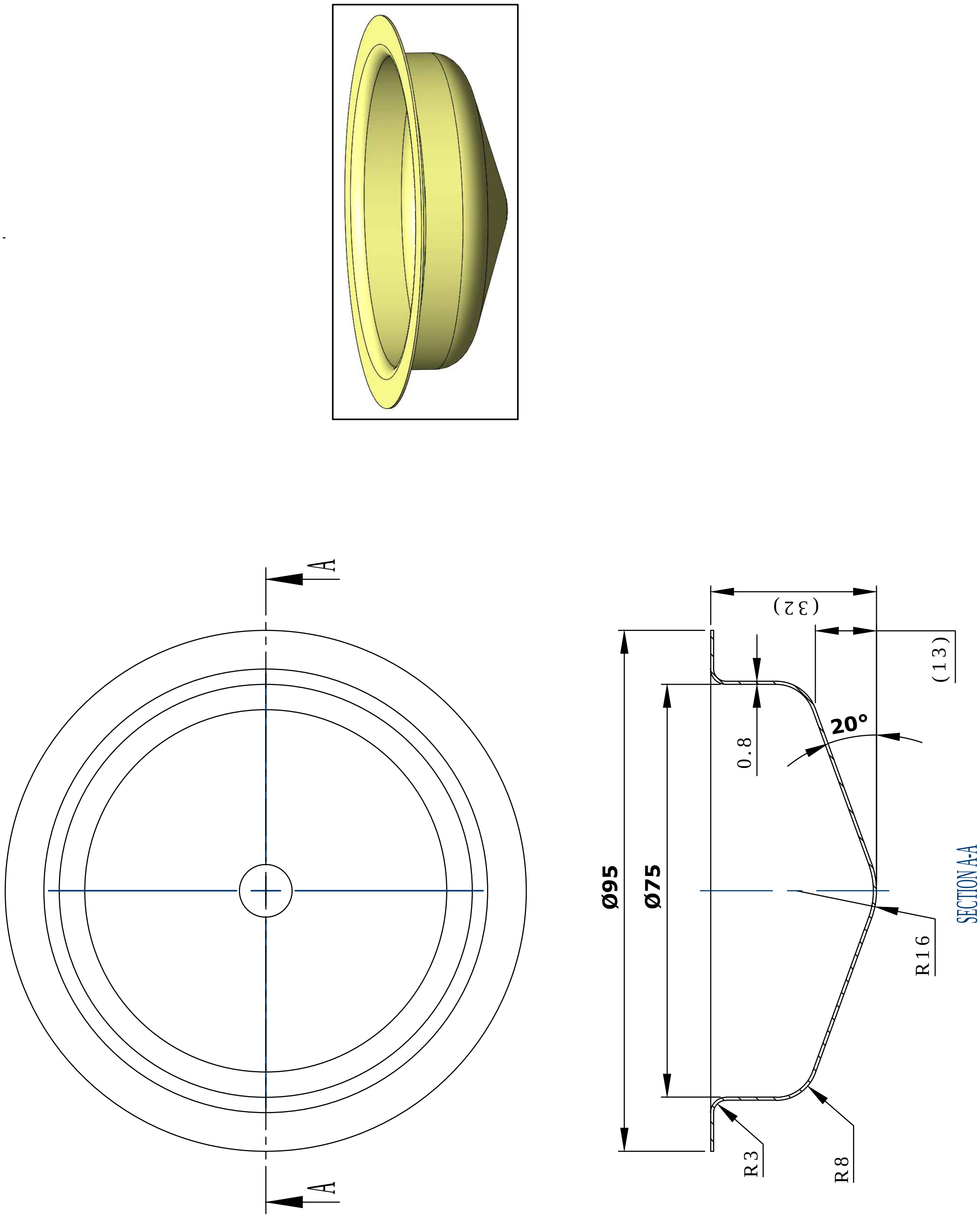


Figure A.4: SS-304 Cup

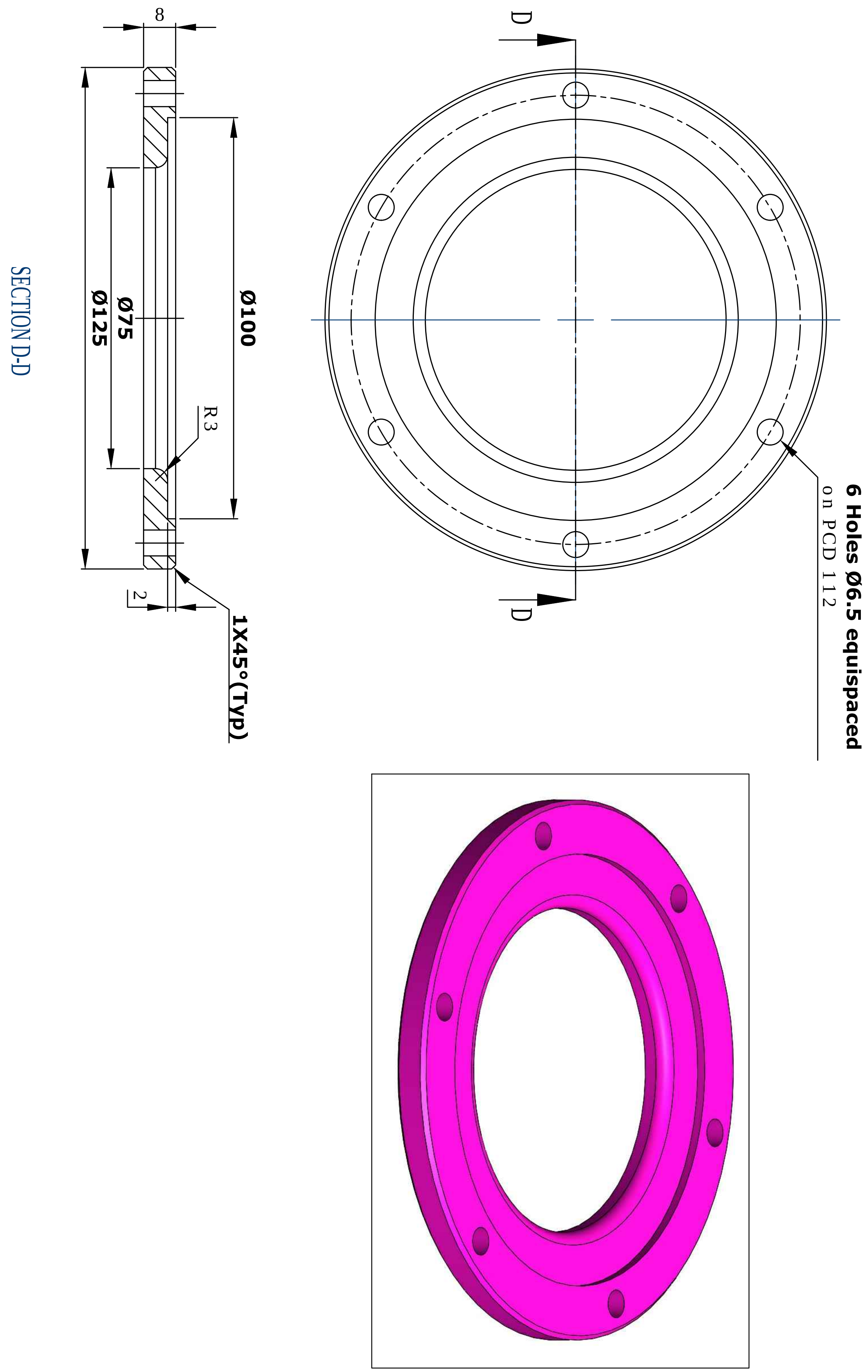


Figure A.5: Die Block

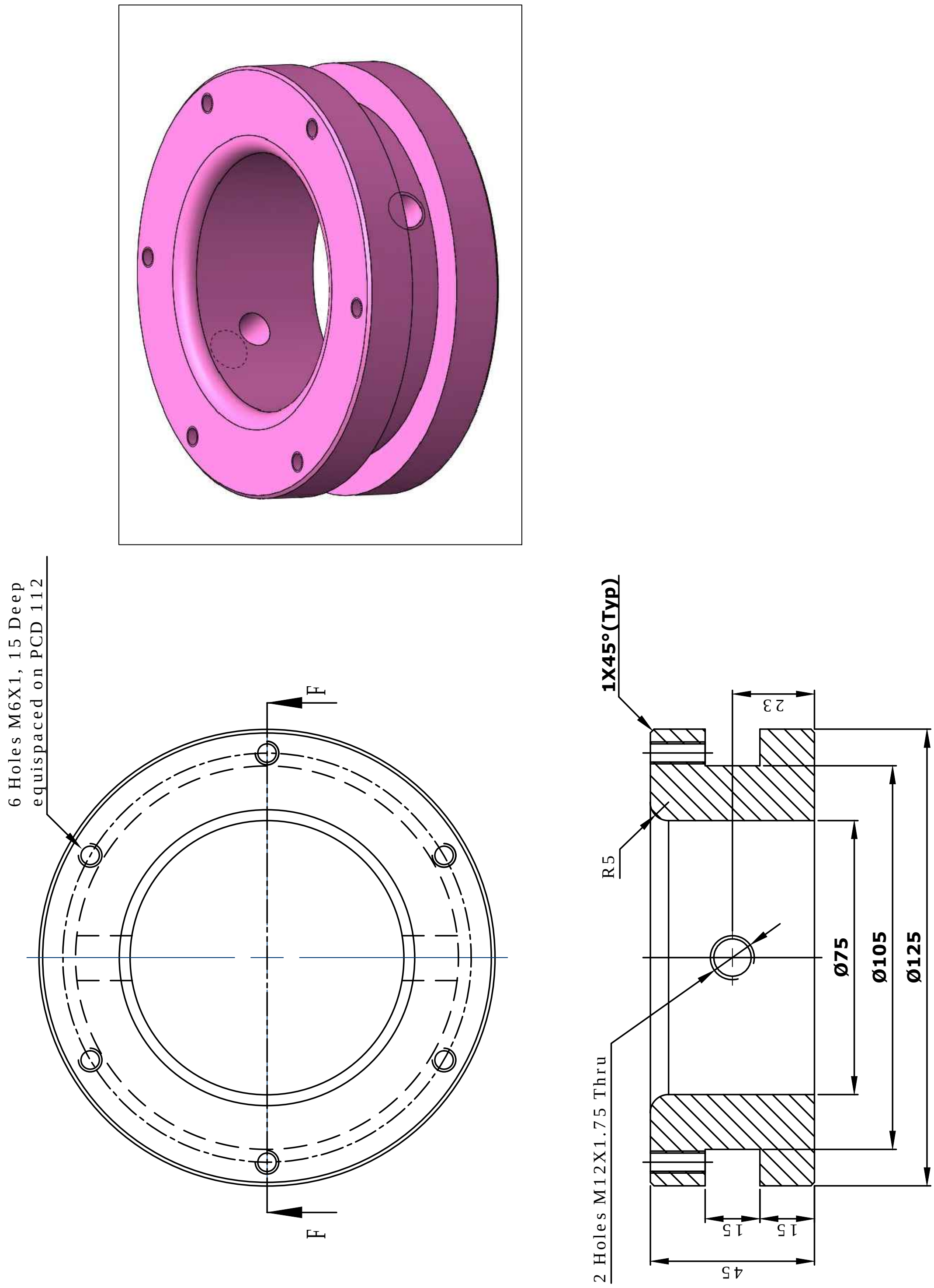


Figure A.6: Fluid Chamber

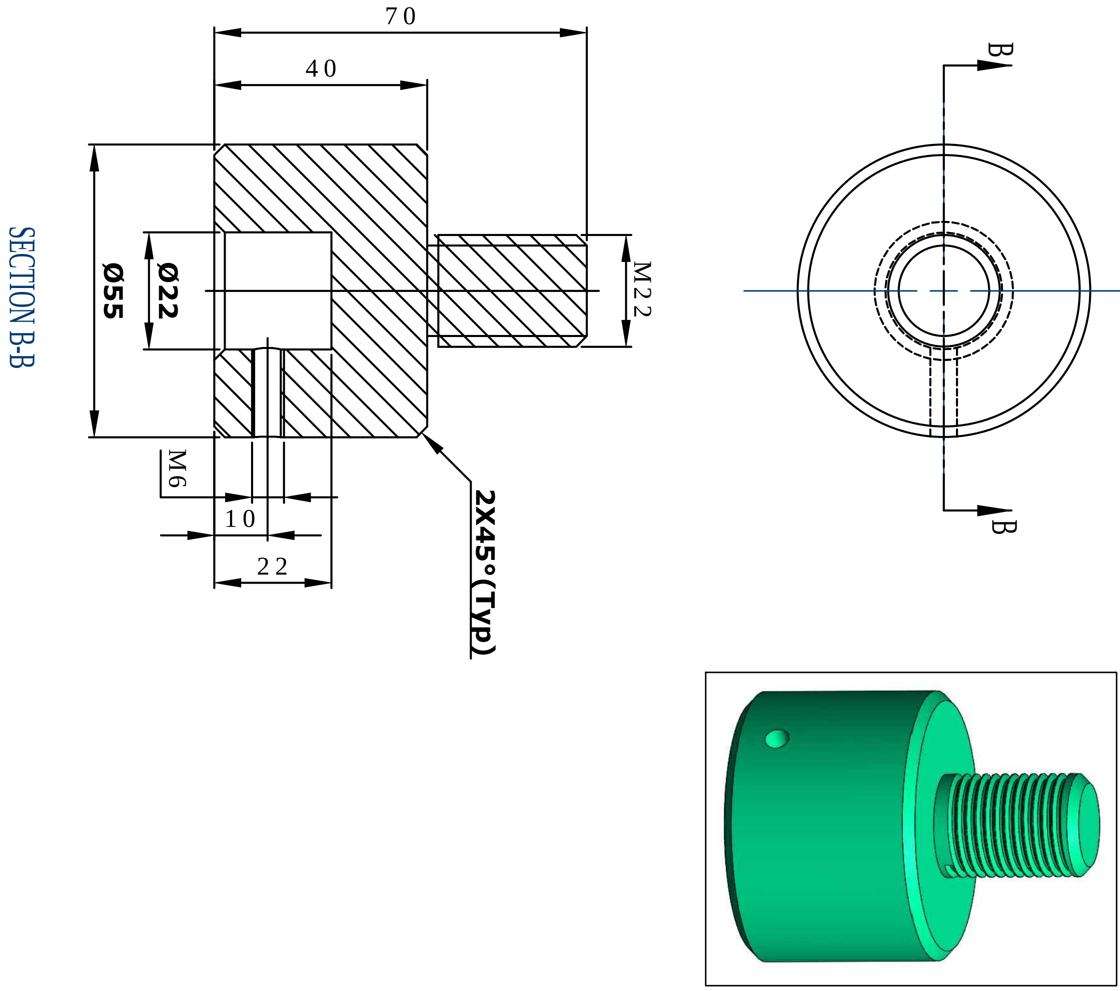


Figure A.7: Lower adaptor

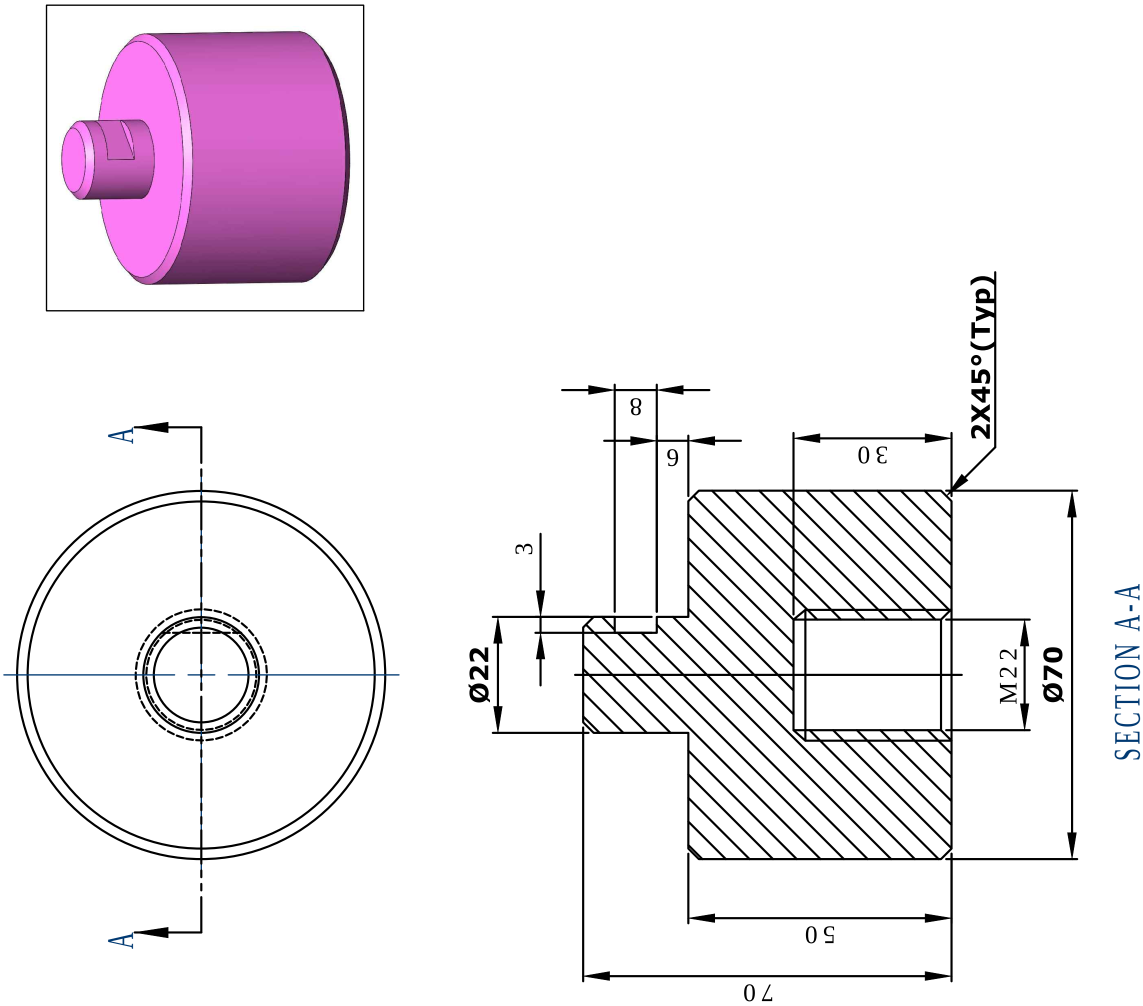


Figure A.8: Upper Adaptor

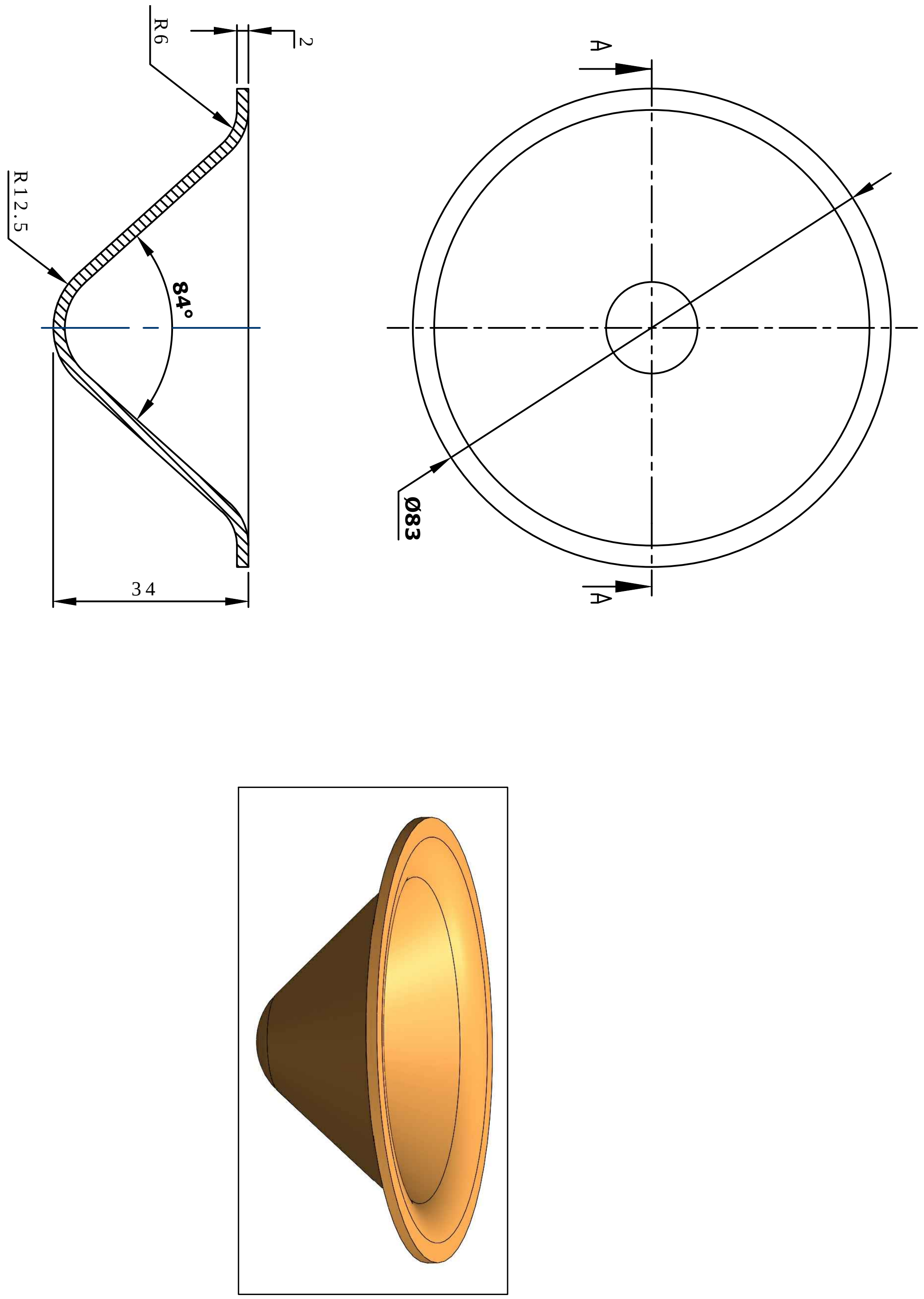


Figure A.9: Punch (84º)

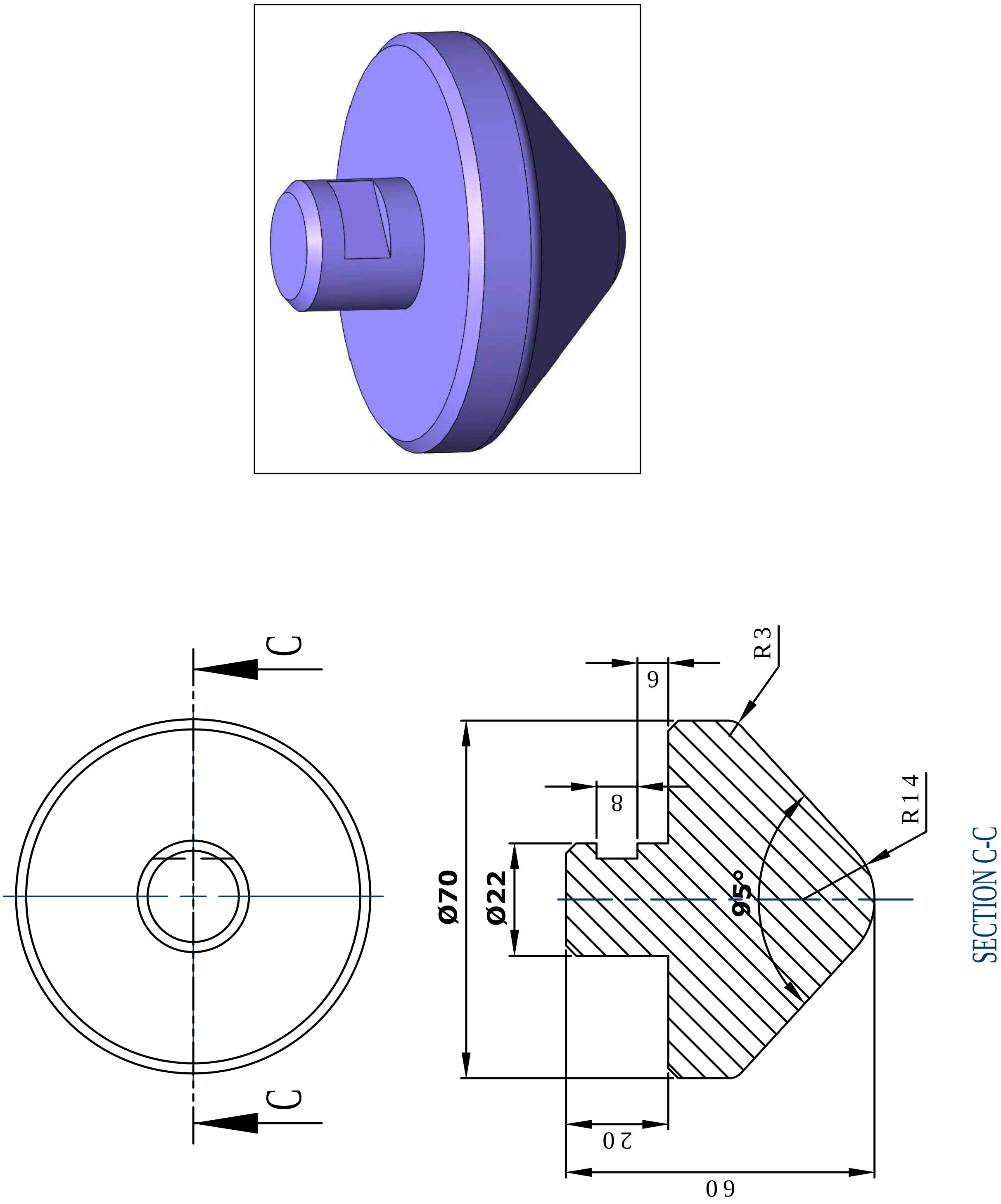


Figure A.10: Punch (95°)

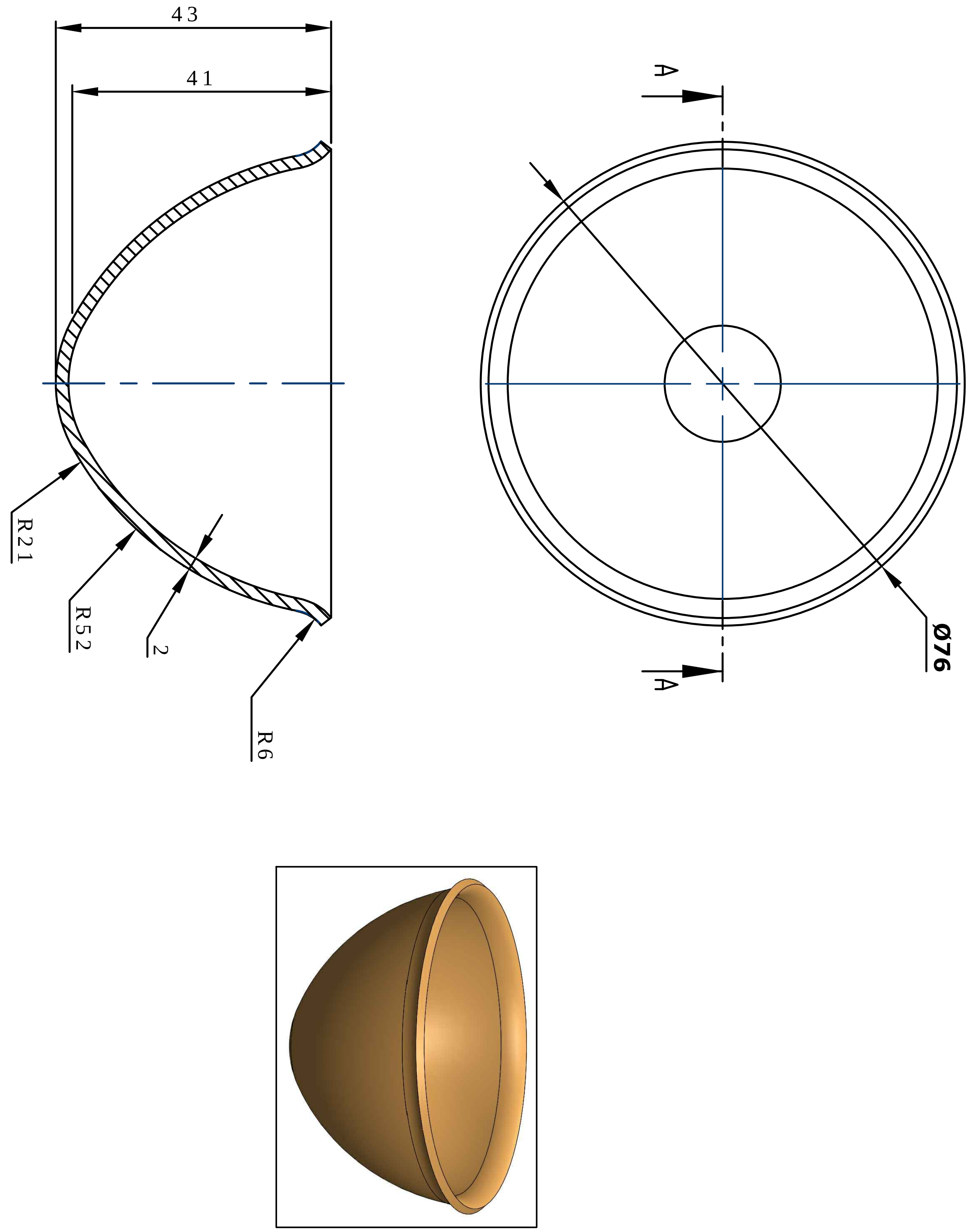


Figure A.11: Spherical Cup

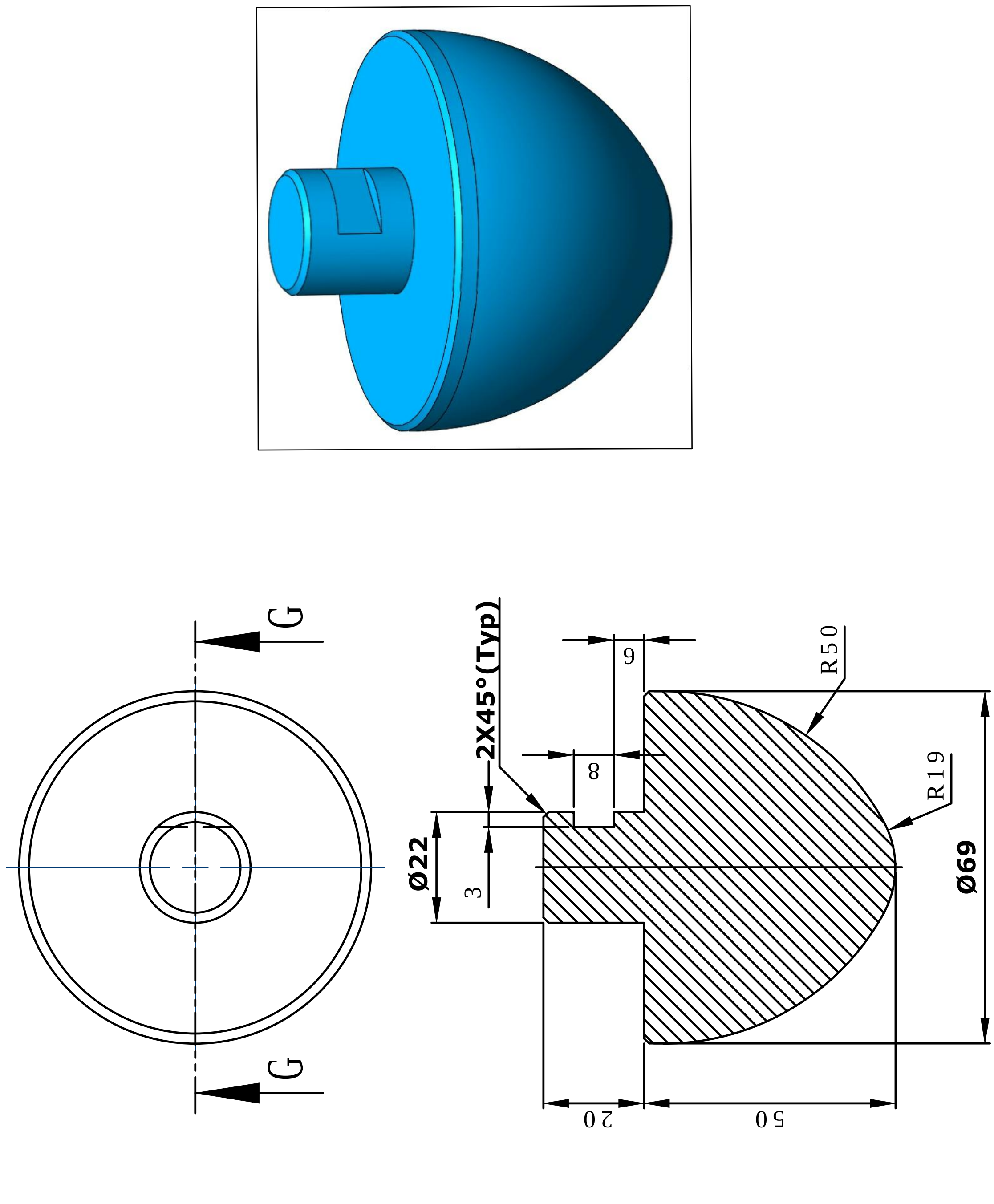
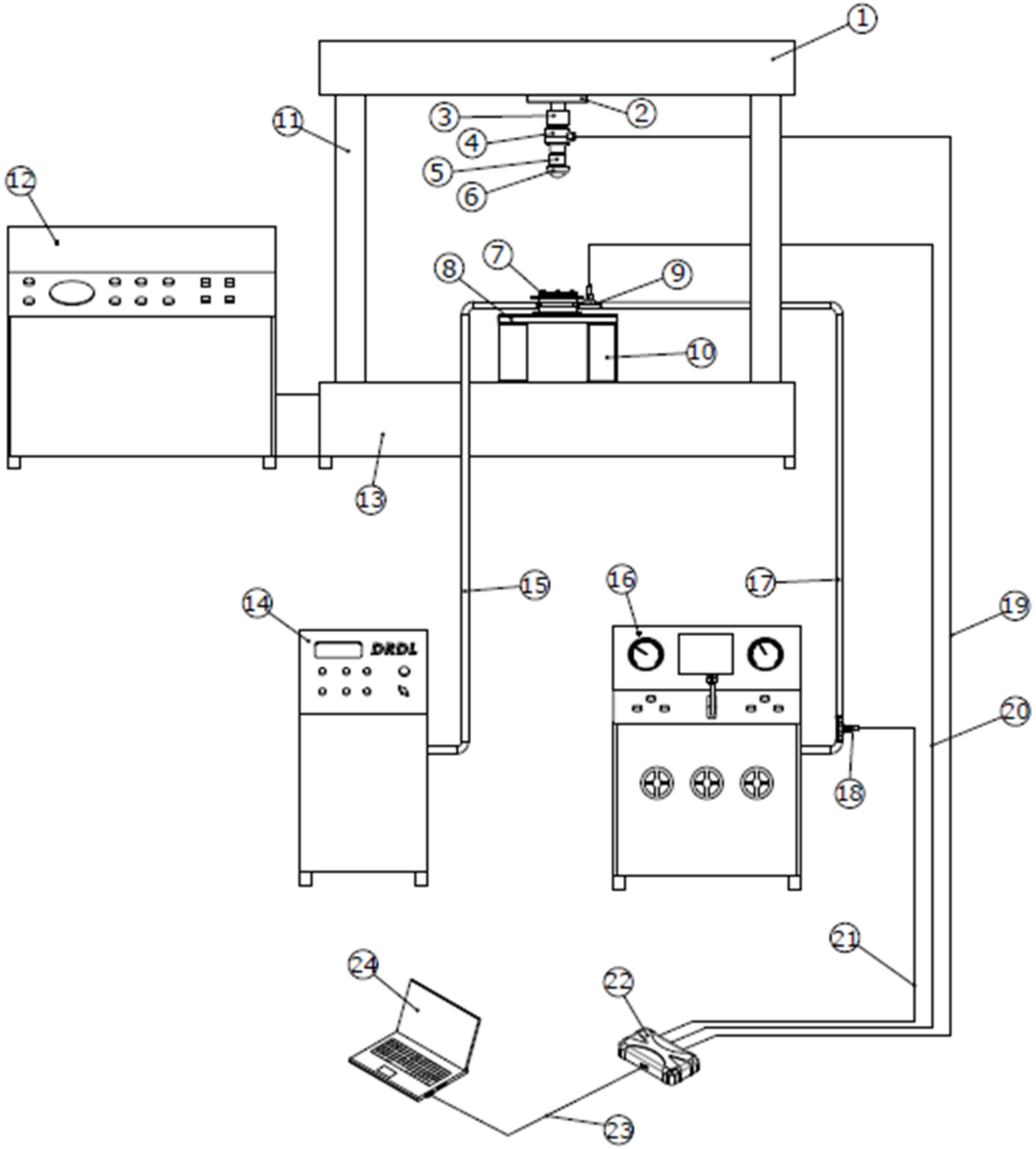


Figure A.12: Spherical Punch



Sl. No.	Component Name
1	Press M/C Ram
2	Top Clamping Plate
3	Upper Adaptor
4	Load Cell
5	Lower Adaptor
6	Punch
7	Die Assembly
8	Bottom Clamping Plate
9	Pressure Transducer-1
10	Riser Block
11	Press M/C Guide Pillar
12	Press M/C Hydraulic Controller
13	Press Machine Bolster
14	Hydraulic Power Pack-1
15	Fluid Inlet Hose
16	Hydraulic Power Pack-2
17	Fluid outlet Hose
18	Pressure Transducer-2
19	Data Collecting Cable(Load Cell)
20	Data Collecting Cable(PT-1)
21	Data Collecting Cable(PT-2)
22	Data Acquisition System(DAS)
23	DAS Data Cable
24	Monitor(CATMAN Software)

Figure A.13: RBSH test set-up

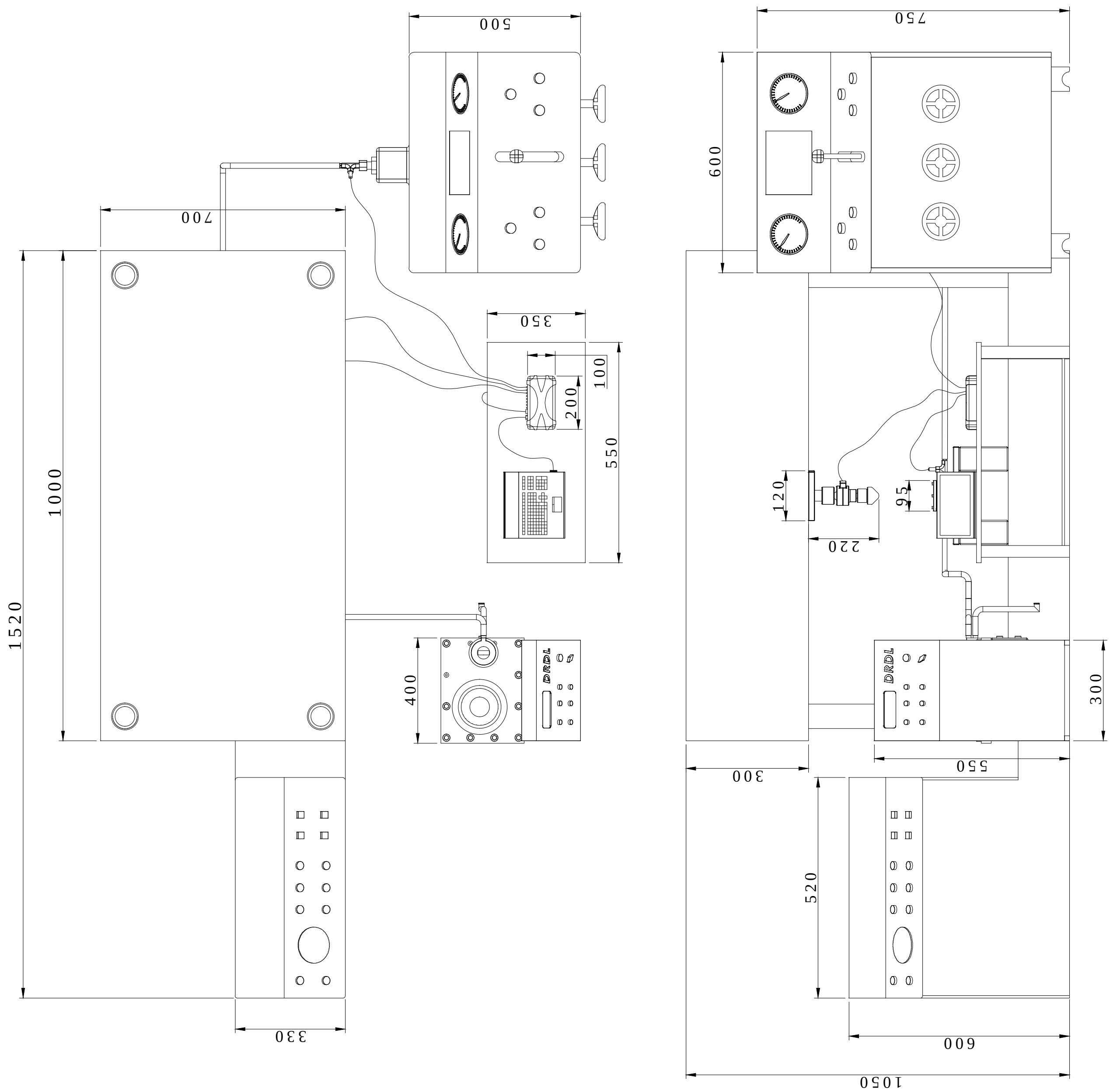


Figure A.14: RBSH test set-up (Top and Front View)

Appendix B

Formulation for Dynamic Explicit Finite Element Analysis

The explicit dynamics procedure performs a large number of small time increments efficiently. An explicit central-difference time integration rule is used in Abaqus; each increment is relatively inexpensive (in comparison to the direct-integration dynamic analysis) because there is no solution for a set of simultaneous equations. The explicit central-difference operator satisfies the dynamic equilibrium equations at the beginning of the increment, t; the accelerations calculated at time t are used to advance the velocity solution to time $t + \frac{\Delta t}{2}$ and the displacement solution to time $t + \Delta t$.

The explicit dynamics analysis procedure is based upon the implementation of an explicit integration rule together with the use of diagonal (”lumped”) element mass matrices. The equations of motion for the body are integrated using the explicit central-difference integration rule

$$\dot{u}^N_{\left(i+\frac{1}{2}\right)} = \dot{u}^N_{\left(i-\frac{1}{2}\right)} + \frac{\Delta t_{(i+1)} + \Delta t_i}{2} \ddot{u}^N_{(i)} \tag{B.1}$$

$$u^N_{(i+1)} = u^N_{(i)} + \Delta t_{(i+1)} \dot{u}^N_{\left(i+\frac{1}{2}\right)} \tag{B.2}$$

where u^N is a degree of freedom (a displacement or rotation component) and the subscript i refers to the increment number in an explicit dynamics step. The central-difference integration operator is explicit in the sense that the kinematic state is advanced using known values of $\dot{u}^N_{(i-1/2)}$ and $\ddot{u}^N_{(i)}$ from the previous increment. The explicit integration rule is quite simple but by itself does not provide the computational efficiency associated with the explicit dynamics procedure. The key to the computational efficiency of the explicit procedure is the use of diagonal element mass matrices because the accelerations at the beginning of the increment are computed by

$$\ddot{u}^N_{(i)} = \left(M^{NJ}\right)^{-1}\left(P^J_{(i)} - I^J_{(i)}\right) \tag{B.3}$$

where M^{NJ} is the mass matrix, P^J is the applied load vector, and I^J is the internal force vector. A lumped mass matrix is used because its inverse is simple to compute and because the vector multiplication of the mass inverse by the inertial force requires only n operations, where n is the number of degrees of freedom in the model. The explicit procedure requires no iterations and no tangent stiffness matrix. The internal force vector, I^J , is assembled from contributions from the individual elements such that a global stiffness matrix need not be formed.

The explicit procedure integrates through time by using many small time increments. The central-difference operator is conditionally stable, and the stability limit for the operator (with no damping) is given in terms of the highest frequency of the system as

$$\Delta t \leq \frac{2}{\omega_{\max}} \tag{B.4}$$

With damping, the stable time increment is given by

$$\Delta t \leq \frac{2}{\omega_{\max}}\left(\sqrt{1+\xi^2_{\max}} - \xi_{\max}\right) \tag{B.5}$$

where $\xi_{\max}$ is the fraction of critical damping in the mode with the highest frequency. For explicit analysis, introducing damping to the solution reduces the stable time increment. In Abaqus/Explicit software, a small amount of damping is introduced in the form of bulk viscosity to control high frequency oscillations.

Appendix C

List of Publications

1. A Kumar, S Kumar, Dasharath Ram, "*Comparative Numerical And Experimental Investigation Of Conventional Deep Drawing And Rubber Assisted Forming Cup Made Up Of Stainless Steel304*", International Journal of Mechanical and Production Engineering Research and Development, Vol. 8, Issue 3, Jun 2018, 743-754

2. A Kumar, S Kumar, Dasharath Ram, "*Comparative formability study of natural rubber, B-nitrile rubber and silicon rubber in rubber assisted forming of hemispherical copper cup*", International Journal of Mechanical and Production Engineering Research and Development, Vol. 8, Issue 4, Aug 2018, 269-278

3. A Kumar, S Kumar, Yadav D R,"Review Of Rubber Based Sheet Hydroforming Processes", 5th International & 26th All India Manufacturing Technology, Design and Research Conference (AIMTDR 2014) December 12^{th}-14^{th}, 2014, IIT Guwahati, Assam, India