DESIGN OF A CROSS SECTION REDUCTION EXTRUSION TOOL FOR SQUARE BARS

A Thesis

by

BOLARINWA O. ONIPEDE

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

December 2005

Major Subject: Mechanical Engineering

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Approved by:

Chair of Committtee,	Karl T. Hartwig
Committee Members,	William Schneider
	Terry Kohutek
Head of Department,	Dennis O'Neal

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ABSTRACT

Design of a Cross Section Reduction Extrusion Tool for Square Bars.

(December 2005)

Bolarinwa O. Onipede, B.S., Texas A&M University

Chair of Advisory Committee: Dr. Karl T. Hartwig

The objective of this project is to design a tool for moderate cross section reduction of bars that are deformed within a channel slider tool that is used for equal channel angular extrusion (ECAE). The bars that are deformed via ECAE have an initial square cross section with a nominal value of 1.00 in^2 and aspect ratios (length/width) ranging between 4 and 6. A systems engineering design methodology is used to generate a top-bottom approach in the development of the tool's design. This includes defining a need statement, which is the "Need for an area reduction extrusion tool to replace the current practices of machining ECAE processed billets". The system functions and requirements are defined next and used to generate three concepts that are compared to select the winning concept for further refinement. Major components of the selected tool are: a container, ram, base plate, punch plate, four die-inserts, four wedges and four flange locks. For materials, such as copper (C10100) and aluminum (Al6061-T6), that can be processed by this tool, the upper bound extrusion pressure, which is derived by limit analysis, is set at 192 ksi. The upper bound extrusion pressure is constrained by the buckling limit of the ram, which is 202 ksi. The maximum wall stress experienced by the container is 113 ksi. For materials with the same cross section and dimensions, fixed end conditions of the Ram support larger bucking loads when compared to other end conditions such as rounded ends or rounded-fixed ends. With the application of the upper bound method, an increase in the extrusion ratio of the tool causes a corresponding rise in the optimal cone angle of the die further translating to a rise in the extrusion pressure.

DEDICATION

To my parents, brother and sisters

ACKNOWLEDGEMENTS

I would like to express my deepest gratitude to my advisor, Dr. K.T. Hartwig, for his patience and direction throughout my graduate research efforts. He has inspired me to challenge myself further and continue to explore the world of materials science. Your thoughtfulness and support during my undergraduate experience has been critical to my current educational achievement. Also, my sincere gratitude is expressed to Drs. Schneider and Kohutek for assistance and direction during the course of my research. I have gained so much from the knowledge and experience that you have shared.

I would also like to thank Robert Barber. You mean so much to me and the success of my graduate work. Your willingness to put aside other assignments in order to assist with explaining the practical aspects of my research will always be remembered. In addition, I would like to thank Suveen Mathaudu and Jae-Taek Im for being great colleagues and guiding me through my graduate curriculum.

TABLE OF CONTENTS

Page

LIST OF FIGURES

LIST OF TABLES

TABLE Page

1. INTRODUCTION

1.1 *Background*

The majority of deformation processes in manufacturing rely on plastic deformation to create shape changes and alter the microstructure of a workpiece (billet) [1]. Deformation processes can be grouped according to the size and shape of the workpiece. As such, deformation processes can be classified as either bulk deformation processes or sheet forming processes. Bulk deformation processes are characterized by small surface to volume ratio, while sheet-forming processes are characterized by high surface area to volume ratio. Extrusion, rolling, forging and drawing are conventional bulk deformation processes, while deep drawing and shearing are examples of sheet-forming processes.

The strength of a material is a critical factor that comes into play during material selection. Bulk deformation processes are used to improve mechanical properties such as the strength and toughness. There are limitations to the use of conventional bulk deformation processes such as extrusion in achieving structure alteration and material strengthening. These limitations are a consequence of the processing technique and material responses, which rely on moderate to large area reduction of the workpiece to achieve significant improvement in the strength of the material. As such, extensive forces are needed to deform the workpiece to strengthen the material. In addition, there is often the occurrence of non-uniformity of the strain within the work piece due to the multiple area reductions typically needed to attain desired mechanical properties. To overcome these drawbacks, new methods of metalworking are needed to address the inherent problems of conventional bulk deformation processes. Severe plastic deformation (SPD) processes such as equal channel angular extrusion (ECAE), multi-axis forging and torsion-compression have been introduced to deal with the shortcomings of conventional bulk deformation processing.

This thesis follows the style of Journal of Engineering Materials and Technology.

1.1.1 Description of ECAE

ECAE is an SPD process that involves the deformation of a well-lubricated billet through a die that has two intersecting channels at an angle 2φ. ECAE was developed by Segal [2] in the former Soviet Union; the concept was first published clearly in the widely distributed open literature in the 1990's. Plastic deformation by ECAE is based on simple shear, which occurs when the workpiece is deformed as it passes through the region of intersection between channels. The amount of strain imposed on the billet as it is deformed is dependent on the angle 2φ. Figure 1 illustrates the process of element transformation during ECAE as the billet moves from the inlet to the outlet channel of the tool.

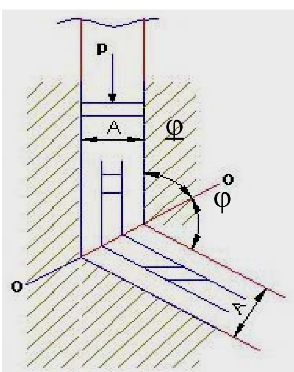


Fig. 1 Schematic of equal channel angular extrusion showing element transformation under simple shear [2]

Some technological advantages of ECAE over conventional bulk deformation processes include the ability to deform materials under constant cross-section area of the workpiece before and after deformation and the development of different structures and textures in the material by altering the orientation of the billet between extrusion passes. In addition, the process can be repeated multiple times on the same billet to take advantage of additional strain imposition. Prior research has shown the total strain intensity after N passes to be [3]:

$$\epsilon_n = N\Delta\epsilon_i \quad (1)$$

where ϵ_n is the total strain intensity, N the number of passes and $\Delta\epsilon_i$ the incremental strain intensity that the material undergoes after each pass.

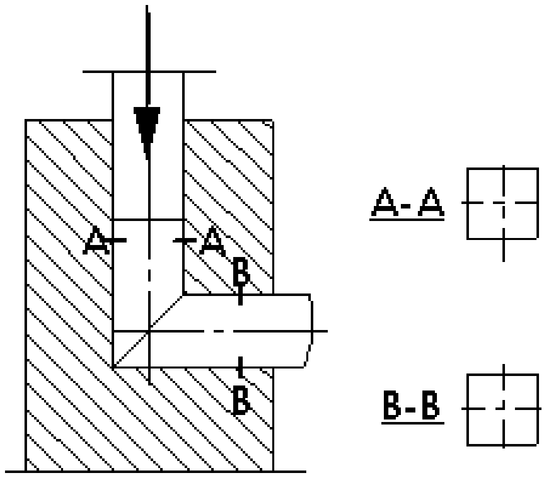
Multi-pass ECAE processing is done to take advantage of additional strain imposition from each pass of the billet through the ECAE tool. It is possible to generate different microstructures within a billet by changing its orientation within the inlet channel prior to additional ECAE processing.

1.1.2 ECAE processing routes

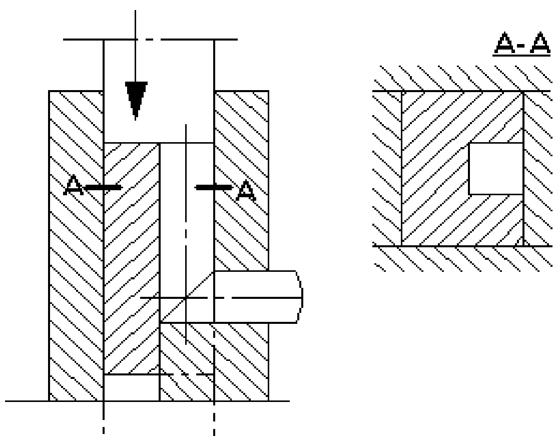
Due to the inherent nature of the ECAE process, certain portions of the billet such as the end portions do not undergo any plastic deformation. As such, the processing route that is selected affects the geometry and volume fraction of the fully worked region. Typical processing routes that are used include Routes A, B, C and B_C [2]. For Route A processing, the billet retains its orientation within the inlet channel after each pass. Route B processing involves the alternate rotation of the billet by ± 90° around the main axis after each pass. Route C is characterized by a 180° rotation of the billet after each pass, while Route B_C involves rotation of the billet by +90° around the main axis in the same direction after each pass. Barber et al have determined that Route C processing creates the largest volume percent of fully worked material [4].

1.1.3 ECAE tool design configurations

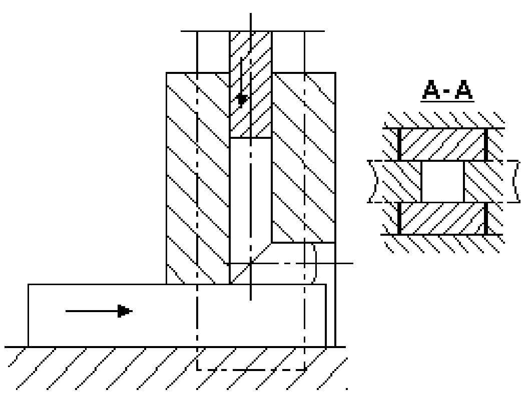
Current ECAE tool designs depend on several factors some of which include; material type, geometry of the billet, aspect ratio of the billet, contact friction, punch pressure and temperature of deformation. The internal design of a tool is primarily dictated by the shape of the billet to be extruded. The most common tool design is made of a solid die block with the two intersecting channels and a punch. Other configurations include a Side/Bottom Sliders design and a Channel Slider design. All three tool designs have their inlet and outlet channels oriented at 90° to each other, which provides effective strain of 1.15 per extrusion pass [3]. Although all three designs possess certain similarities, the control of contact friction between the billet and the tools' channels highlights their differences. The Side/Bottom Sliders design has two side walls that move along with the billet in the first channel. As such, friction is reduced dramatically when compared to the solid die block design. In addition to the two moveable walls, there is a bottom wall that moves the billet into the second channel. The third design configuration, referred to as the Channel Slider design has three moveable walls that are fabricated into a single slider that moves along with the billet in the first (inlet) channel. Figure 2 illustrates the three design configurations, while the pros and cons of each configuration are presented in Table 1.



(a)



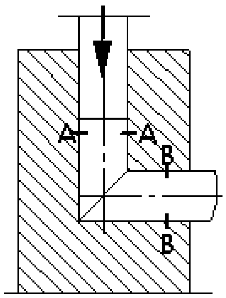
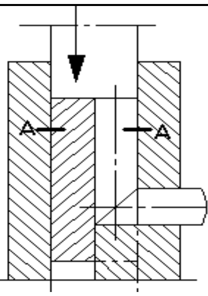
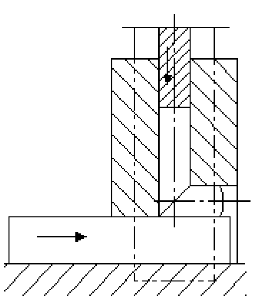
(b)



(c)

Fig. 2 Three ECAE tool designs: (a) solid tool block, (b) channel slider tool with 3 moveable walls within inlet channel, (c) side/bottom slider tool with 2 moveable walls in inlet channel and moveable bottom within outlet channel [2]

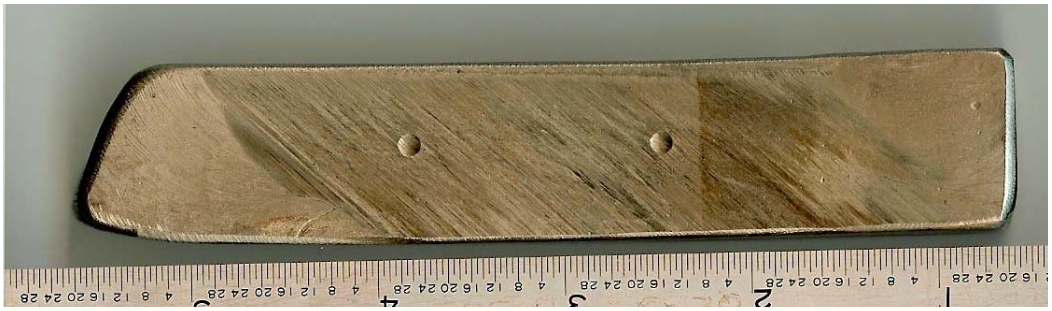
Table 1 Comparison of three possible ECAE tool configurations

	PROS	CONS
SOLID BLOCK TOOL DIE	➢ Can be easily manufactured (low cost).	➢ High contact friction due to sliding motion of billet on all walls of the first channel.
	➢ Billet does not require reworking for subsequent extrusions.	➢ A second extrusion or device is required to eject billet from second (outlet) channel.
	➢ Simplicity of design.	➢ Low buckling limit of punch due to high contact friction and slenderness ratio of punch.
	➢ Heating system can be easily incorporated if needed.	➢ Billet aspect ratio (length/diameter) is limited to 4-5 for 90° die angle
	➢ Better temperature controls (no moving walls).	
CHANNEL SLIDER	➢ Billet geometry remains relatively unchanged.	➢ Billet ejection may be different.
	➢ Low contact friction due to moveable walls in first channel.	➢ High manufacturing costs due to number of parts and complexity of design.
	➢ Extremely high buckling limit of punch.	➢ Some flash is formed between billet and tool.
	➢ Cleaning of tool is easy due to easy disassembly of components.	➢ Traveling hot zone due to moveable walls (uniform heating problem)
SIDE/BOTTOM SLIDER	➢ Billet ejection process is easy to perform.	➢ High tool cost due to number of components and complexity of design.
	➢ Simple to manufacture.	➢ Inability to heat all surfaces uniformly.
	➢ Low contact friction between tool and billet.	➢ Billet must be reworked to its original geometry for multi-pass extrusions with certain ECAE processing routes.
	➢ Billet aspect ratios greater than 10 can be extruded.	

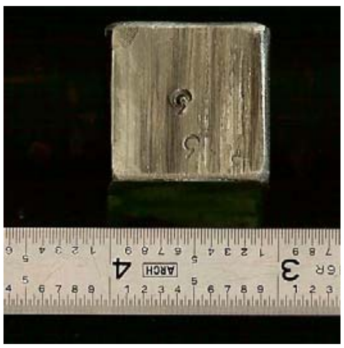
1.2 *Problem Statement*

The processing of square cross section billets by Equal Channel Angular Extrusion (ECAE) is currently done at Texas A&M University with a tool that has side-sliding walls and a bottom slider. This tool accepts billets that have an initial nominal square cross sectional area of 1.00in^2. Also, the billets have high aspect ratios, typically between 4 and 6. The purpose of the tool's sliding walls is to minimize the contact friction generated during the deformation of the billet within the inlet channel. The walls of the inlet and outlet channels of this tool design are shaped into square cross sections of near equal size to enable ideal ECAE, which is a process that imparts uniform simple-shear to the bulk material. While the concept of the sliding walls in the tool design has created a reliable tool with low friction, a shortcoming of this design is reflected in the geometrical change of the billets that emerge from the outlet channel of the tool. The deformation and curvature associated with typical billets are shown in Figure 3. In addition, typical geometrical sizes of ECAE processed billets are presented in Table 2.

Billets of initial square cross-section that are processed by this tool design end up with a rectangular cross section that is larger than the initial size in addition to the burrs that form along the edges of the billet. The change in shape and size of the billet is a consequence of the ECAE tool design, which necessitates a clearance between the sliding walls and bottom leg of the tool coupled with elastic deformation of both the tool and billet during ECAE processing. As such, a size mismatch occurs between the billet and inlet channel of the ECAE tool for some subsequent multi-pass schedules (routes) after each extrusion. It is possible to eliminate this problem by selecting billets and a solid die block design with appropriate sized channels. The drawback to using the solid die block tool for a 90°-angle die is the limitation of the billet length/diameter ratio by the contact friction that is generated within the inlet channel, which limits the aspect ratio of the billets that can be processed by the tool.



(a)



(b)

Fig. 3 Distorting of billet cross section revealing (a) curvature along the length after ECAE processing with a bottom/side slider tool and (b) final rectangular cross section

Table 2 Typical dimensions of billet with initial square cross-section of 1.00 x 1.00 in^2 after undergoing single pass ECAE processing

Material	Depth (in.)	Width (in)	Height of Curvature (in).	Area after ECAE (in^2)
Cu101	0.950	1.010	0.980	0.9898
Al6061	0.965	1.005	0.984	0.9889
Monel	0.980	1.020	1.138	1.1608

1.3 *Current Solution to Problem*

In order to eliminate the size mismatch that exists between the billet and ECAE tool inlet channel after each extrusion, the billets are currently machined to a size that can be reinserted into the ECAE tool for additional processing. The machining of billets involves processes that ultimately lead to material losses. The first step involves using a grinder to remove burrs that form along the edges of the billet. The second step involves rolling the billet to its initial width by using a rolling mill, while the final step involves milling the rolled bar to reduce the height and square up the cross section. As for the machining of hollow billets that containing powder, deburring followed by milling are the processes utilized to reduce the billet size to fit the inlet channel of the ECAE tool.

1.4 *Shortcomings of Current Solution*

The current machining methods used are material inefficient, time inefficient and expose the operator to operational injuries. For instance, present machining of ECAE deformed billets leads to significant material loss over several cycles of ECAE. A typical billet loses between 0.1-0.2 inches of its length once it has been reshaped. This material loss can significantly impact the results of ECAE processing since multi-pass ECAE processing typically ranges from four to sixteen cycles. As such, a 0.2 inch reduction in the length of a 6 inch billet translates to a 3.3 percentage reduction in the length. It is not uncommon to experience 20 - 50 percent reduction in the length of billets with short aspect ratios after eight-twelve ECAE passes. Also, a significant amount of time is involved in machining the billets for additional ECAE processing. As such, the amount of ECAE processing that can be achieved within a period of time is limited by the reshaping that has to be performed after each pass. This results in underutilization of the ECAE process and increases in the operational costs involved. Furthermore, operator safety is reduced as the number of machining steps requiring direct control increases. A simple in-house device that eliminates material waste and reduces the machining time between extrusions is desired to improve operational efficiency of the ECAE process.

1.5 *Design for Improved Solution*

A systems engineering design approach will be used to address the need posed by the problem statement. This procedure involves the use of a top-down approach in the development of the design and enables decomposition of the problem into small subsystems that are manageable and can be easily analyzed. The steps that are used in the classical design methodology will serve as the guideline to generate a detailed design that addresses the issue raised within the problem statement. The general design process follows a series of steps outlined below:

Need → Need Analysis → Function Structure → Functional requirement → Performance requirement → Conceptual design → Preliminary design → Final design.

1.5.1 Need statement

The need statement is a top-level statement of what must be provided in order for the design to succeed. For the current problem, there is a "Need for an area reduction extrusion tool to replace the current practice of machining ECAE-processed billets, in order to avoid material losses and reduce the time needed to reshape a billet to its original size for additional ECAE processing".

1.5.2 Need analysis

The need analysis is done to understand the nature and scope of the overall problem, with a view towards decomposing the need into top-level functions that the overall design must provide. For the current problem, the area reduction extrusion tool should be able to satisfy the twin challenges of reshaping ECAE processed billets to their initial size and also reducing the time between multi-pass ECAE extrusions. Reshaping of the billets back to their initial size involves; providing the means to accommodate a deformed billet, transmission of force to the billet and constraint during the deformation of the billet. Also, it is necessary to provide the means to reduce the cross section of the billet and then straighten its edges afterwards. Accommodating an ECAE deformed billet is paramount to achieving the goal of area reduction. It involves defining and then incorporating a boundary that will serve as a containment zone for the deformed billet before and after the reshaping process. A device and interface for transmitting force to the billet are necessary to supply the force that will enable motion of the billet within its containment zone. Also important is the ability to contain the material during motion within its containment zone and the region where the actual area reduction occurs. This is because it is assumed that certain physical phenomenon like upsetting of the billet may occur whenever compressive forces are applied to the billet. The process of area reduction in itself relies on the determination of the geometrical change and material type that are needed to transform the shape and size of the billet. Furthermore, straightening of the billet's edges after completing the area reduction is important to the process of achieving multi-pass ECAE processing. Finally, reducing the hold time between multi-pass ECAE processing involves reducing the number of machining processes and creating an interface between the area reduction tool and the extrusion tool. In order to satisfy the need, the area reduction tool should be designed within the bounds imposed by external constraints on the system. These constraints include:

1. Reshaping of the billet at room temperature. This is because ECAE processing with the Side/Bottom Slider tool is often done at room temperature.
2. Geometrical size of the billet after area reduction should not exceed the size of the ECAE inlet channel. As such, the tool will be capable of accommodating the majority of billets and their associated curvatures formed after ECAE processing.
3. The cross sectional area of the inlet channel of the area reduction tool shall not exceed 1.06” by 1.06”. This is done to limit the amount of force needed to deform the billets to achieve the desired area reduction.
4. The device should be capable of reshaping a variety of metals ranging from aluminum to titanium and steel.

1.5.3 Function structure

This is a top-down decomposition of what the system (proposed design) does and the role played by the subcomponents of the system. The function structure begins with the need statement and ends with the functional requirements of the system. The function structure of the system designed to address the current problem is presented in Figures 4a, 4b and 4c in hierarchical order of the top-level functions down to the lowest level. The functional requirements are the lowest level of decomposition of the function structure beyond which it becomes necessary to address how to provide a function. Although the functional requirements are derived from the lowest level of the function structure, they are affected by external constraints that have been imposed on the system.

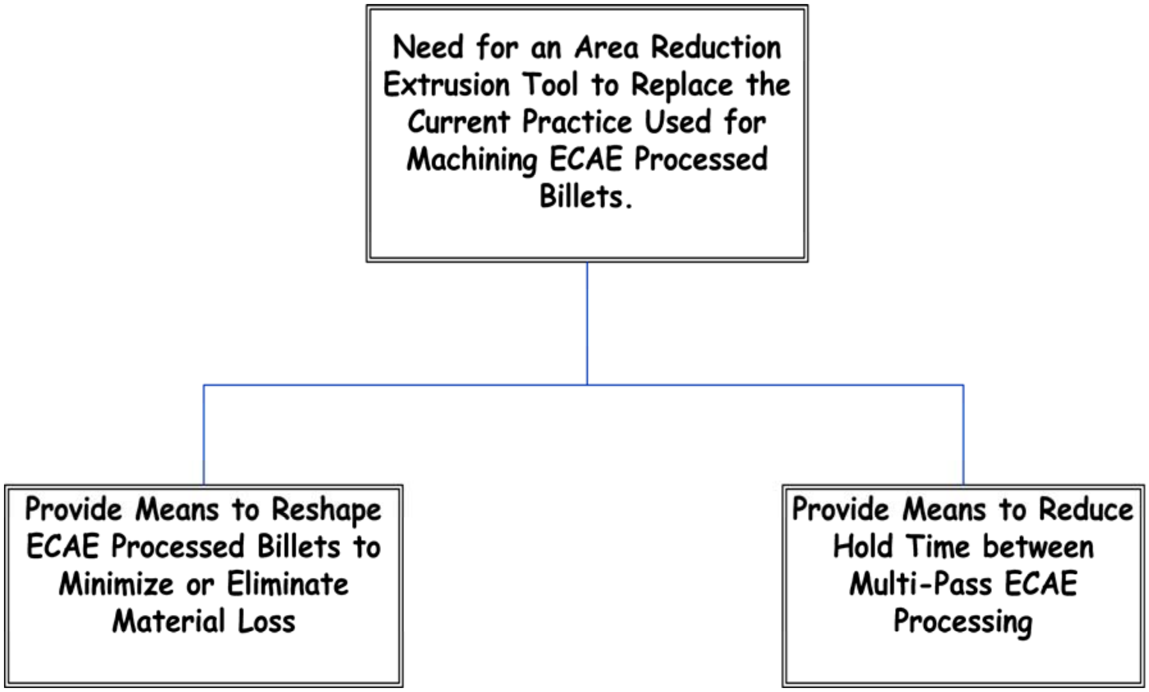


Fig. 4a **Function structure showing top-level functions of the system**

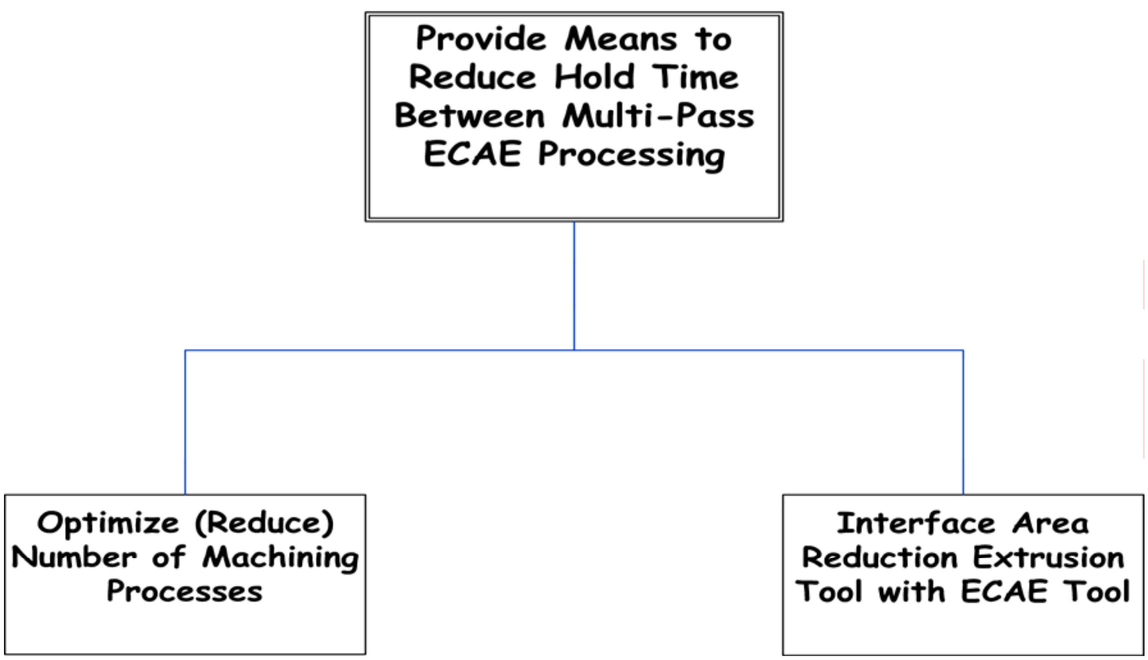


Fig. 4b **Decomposition of function structure – providing means to reduce hold-time between ECAE processing**

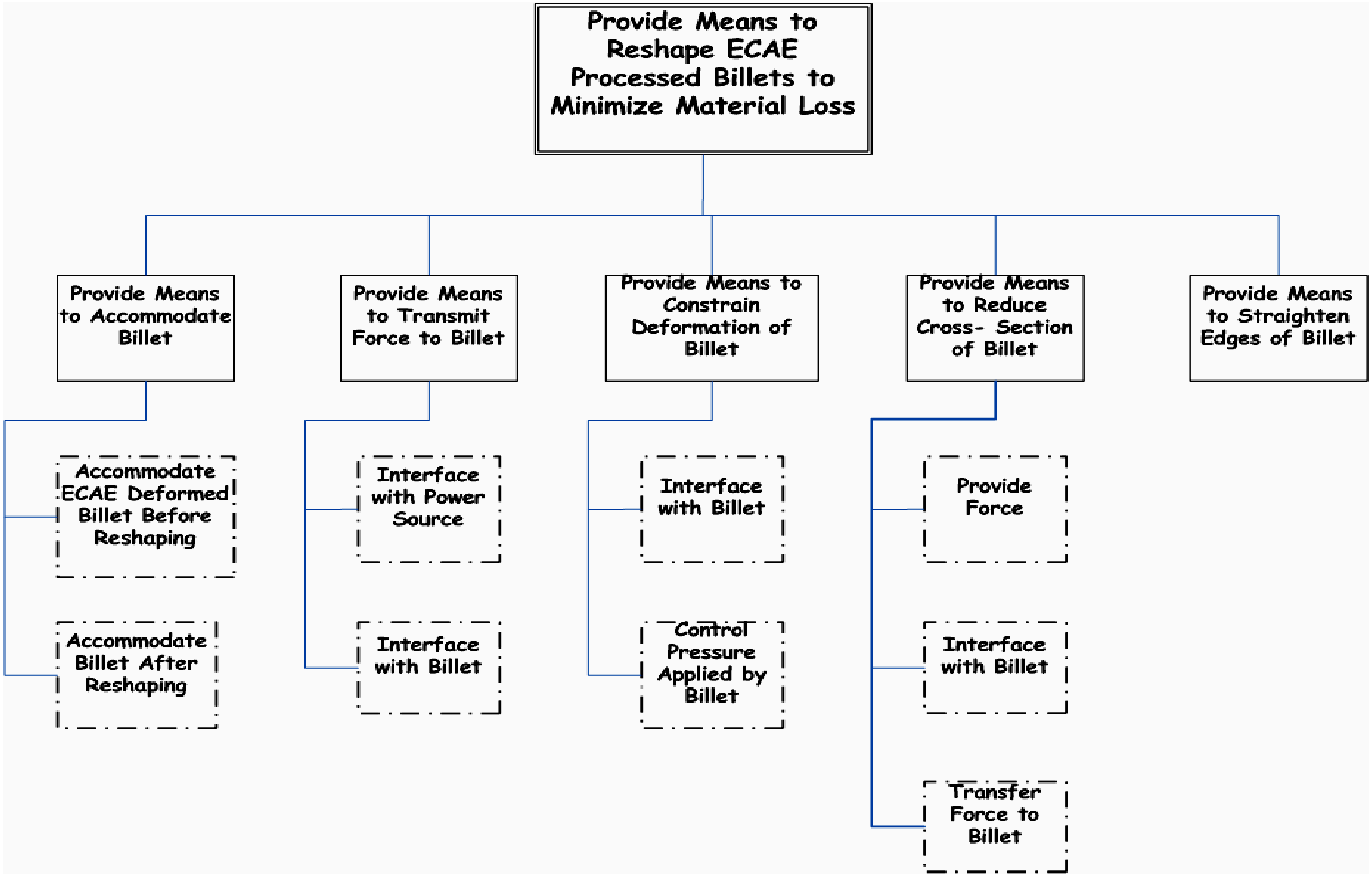


Fig. 4c **Decomposition of function structure – providing means to reshape billet**

2. LITERATURE REVIEW

2.1 *Review of Metal-Working Operations*

Metal working operations refer to the processes that are used to form metals into useful shapes. The processes can broadly be categorized into plastic deformation processes and metal removal or machining processes. Plastic deformation processes are those in which the volume and mass of the metal are conserved and as such metal is displaced from one location to another [5]. On the other hand, metal removal processes involve material removal in order to get the required shape. Plastic deformation processes can further be divided into groups based on factors such as the type of operation, temperature, size and shape of the work piece [1]. For instance, by applying the temperature criterion, plastic deformation processes can be divided into cold and hot working processes. Cold working operations are typically performed at room temperature, while hot working operations are performed at temperatures greater than 0.5 T_M, the hot-working range. Also by considering the type of operation involved, it is possible to divide plastic deformation processes into primary and secondary working operations. Primary working operations are those that take a solid piece of metal (generally from a cast state or powder consolidate) and then break it down into shapes such as slabs, plates and billets [1]. Secondary working operations on the other hand involve further processing into finished products.

Recently, the trend has moved towards classifying plastic deformation processes according to the size and shape of the work piece. Thus all deformation processes are classified as either bulk deformation or sheet forming [1]. Bulk deformation processes are those that involve work pieces with a small surface area-to-volume ratio or surface area-to-thickness ratio. A change in the thickness or cross section of the work piece is indicative of a bulk deformation process. On the other hand, thickness changes are detrimental to sheet-forming processes due to the high surface area-to-volume ratio of the work piece. Rolling, forging and extrusion are bulk deformation processes that will subsequently be described with emphasis on extrusion since it is the technique that will be adopted for use with the area reduction extrusion tool. Although the aim of the majority of bulk forming operations is to produce a desired shape, modification of the material structure and surface characteristics of the work piece usually occur as a result of the deformation process. Certain effects derived from bulk forming operations such as refinement of grain size and improved surface quality may be beneficial. On the other hand, effects such as material discontinuities arising from surface and internal imperfections can easily lead to defective work pieces. Typical imperfections that commonly appear are pits, chevron cracks, laps, inclusions and pores.

2.1.1 Rolling

Rolling involves passing a metal between two rotating rolls that apply compressive forces to reduce the thickness of a work piece. Rolling may be performed as a hot working or cold working process. Rolling lends itself as the most widely used metal working process because it can be used to produce standardized, uniform quality products at low cost [6]. Although deformation of the work piece occurs primarily from the compressive effect of the rollers on the work piece, surface shear stresses exist due to friction between the metal and the rolls. Since the surface velocity of the rotating rolls is greater than that of the incoming metals, the interface friction is responsible for propelling the metal forward through the rolls [6]. This interface friction is also responsible for creating the condition of plane strain that exists whenever a metal is rolled. A schematic representation of rolling is presented in figure 5.

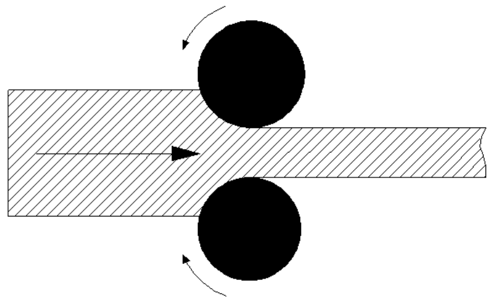


Fig. 5 Cold rolling of a plate [6]

2.1.2 Forging

Forging is another metal working process that relies on localized compressive forces created by hammering or pressing of a metal into a useful shape. Similar to the rolling process, forging may be performed either hot or cold. The three broad categories of forging are open-die forging, impression-die forging and closed-die forging [1]. Open-die forging is performed by placing a solid work piece between two flat dies and then compressing it to reduce the height, an operation typically known as upsetting. As for impression-die forging, the work piece acquires the shape of the die cavities (impression) while it is being upset between the closing dies [1]. Flash is formed during the process and it plays a prominent role in the flow of the metal into the cavities. Closed-die forging is similar to impression-die forging, although no flash is formed because the work piece is completely surrounded by the dies. Since no flash can be formed in this process, proper control of the volume of the work piece is necessary to achieve near-net-shape production. A typical open-die forging operation is shown in figure 6.

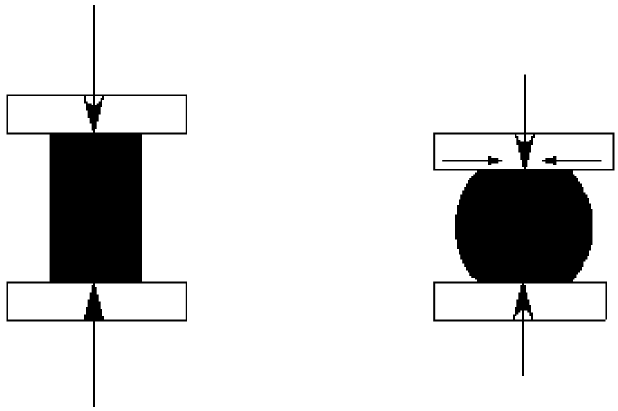


Fig. 6 Open-die forging of a block between two plates [1]

2.1.3 Extrusion

Extrusion refers to the process by which a metal is compressively forced to flow through a die orifice under high pressure. It is a process that is used to produce long, straight, semi-finished metal products such as bars, wires, strips, solid and hollow sections. Extrusion can be performed either hot or cold. Some of the benefits of hot extrusion are:

1. It is used whenever there is the need to reduce extrusion forces.
2. It is typically used to eliminate cold working effects.
3. It is applied whenever there is the desire to reduce directional properties.

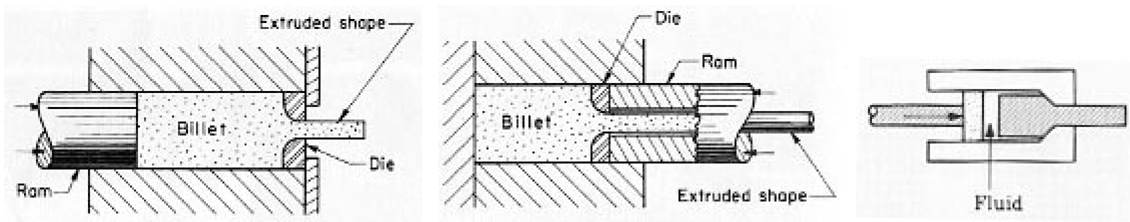
On the other hand cold extrusion, which is an important commercial process, is used because of the following advantages [1]:

1. Improved mechanical properties due to strain hardening, provided that the heat generated by the extrusion does not cause the work piece to recrystallize.
2. Good control of tolerances, thus requiring a minimum of machining operations.
3. Lack of formation of detrimental oxide layers.
4. Improved surface finish provided there is adequate lubrication that is effective.
5. High production rates and economics.

The three basic types of extrusion (Figure 7) are direct extrusion, indirect extrusion and hydrostatic extrusion. Direct extrusion, also known as forward extrusion, is similar to squeezing toothpaste out of the opening of a toothpaste tube. The process involves placing the work piece into a container and then forcing it through the die by a ram/punch. Indirect extrusion, also known as backward or inverted extrusion, involves the motion of the die towards the stationary billet. The extruded product travels in a direction that is opposite that of the die and the ram. Indirect extrusion leads to a lower friction between the billet and chamber walls and this reduces the power required for extrusion when compared to direct extrusion. However there are practical limitations to indirect extrusion created by equipment complexity and the extruded length of the product [6].

In hydrostatic extrusion, the work piece is completely surrounded by a fluid that is sealed off and pressurized sufficiently to extrude the work piece through the die [7]. Because of the pressurized fluid, there is no friction along the container walls since the billet does not upset to fill the bore of the container as it would do in either direct of indirect extrusion. Some of the practical limitations affecting hydrostatic extrusion are [7]:

1. Complexity of the equipment caused by the high pressure involved.
2. Reduced process efficiency in terms of billet-to-container volume ratio.
3. Reduced control of billet speed and stopping due to potential stick-slip and excessive stored energy in the compressed liquid.



(a) (b) (c)

Fig. 7 Basic types of extrusion: (a) direct extrusion, (b) indirect extrusion, (c) hydrostatic extrusion [6]

In order to describe the amount of deformation that a work piece has been subjected to, it is customary to calculate an average strain as either the reduction, r, in area:

$$r = \frac{A_o - A_f}{A_o} \tag{2}$$

or the extrusion ratio, R_E:

$$R_E = \frac{A_o}{A_f} \tag{3}$$

where; A_o is the original cross section of the billet and A_f the cross section of the extruded billet. From the extrusion ratio, it is possible to compute the absolute value of the true strain, ε;

$$\varepsilon = \ln\left(\frac{A_o}{A_f}\right) = \ln R_E \tag{4}$$

2.2 *Relevant Factors and Equations*

For extrusion, factors such as the mechanical properties of the material, friction, extrusion ratio, working temperature and die profile are important parameters that affect the finished product and influence the extrusion force. The optimization of these factors is a critical task for researchers and tool designers. Analytical expressions will be presented within this section to serve as the basis for computing critical engineering calculations later on within the results section. A critical engineering calculation necessary is the determination of the minimum extrusion force to create material flow. This force influences the overall design of the extrusion tool in terms of the wall thickness, material selection and the components needed to transmit the force.

2.2.1 Methods of analysis of extrusion pressure

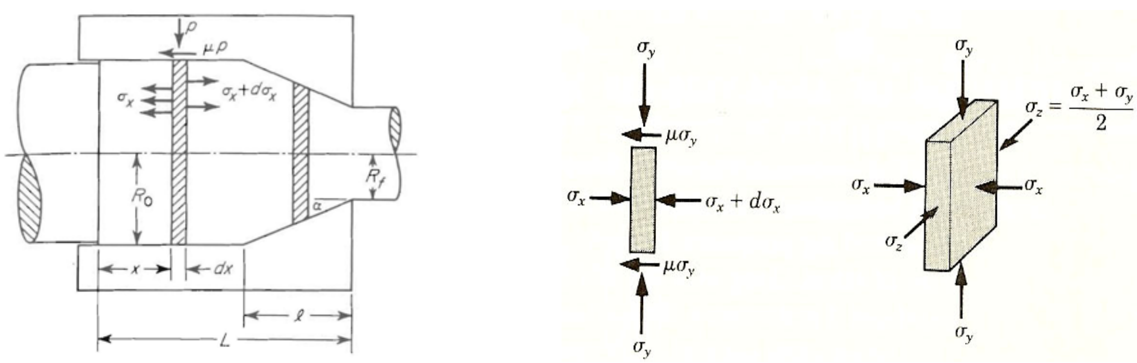
The extrusion pressure is an important factor that drives the design of the area reduction extrusion tool. Knowledge of the extrusion pressure is critical to designing for the punch buckling limit, appropriate tool size and chamber wall thickness. Several approaches have been developed to analyze the loads and stresses arising from metalworking processes. The major analytical methods available used for deformation processing of a work piece are the slab method, slip-line analysis, and limit analysis. Numerical methods such as finite-difference and finite-element methods have been developed as well. Since exact solutions of load requirements are seldom predictable due to the effects of friction and inhomogeneity of deformation of the work piece, the methods of analysis mentioned so far rely on simplifying assumptions that provide approximations of the exact analytical solution. The slab method, slip-line techniques and limit analyses have provided approximate solutions, while the finite difference and finite element methods are numerical [8].

The slab method of analysis, also known as the free body-equilibrium approach, is applied by isolating an element within a work piece. This is followed by performing a force balance (both normal and frictional) on the element to generate a differential equation that can be solved to estimate the extrusion load. The following important assumptions are made with respect to the slab method of analysis [9]:

1. "Direction of the applied load and planes perpendicular to this direction define the principal directions and the principal stresses also do not vary on these planes".

2. “Although the effects of surface friction are included in the force balance, these do not influence internal distortion of the work piece or the orientation of the principal directions”.
3. “Plane sections remain plane. As such, deformation is homogenous with regard to the deformation of induced strain”.

For the case of simple compression with friction, the decrease in the length of the billet during compression causes lateral expansion of the other sides of the billet, which is considered to be incompressible (constant volume). For the element shown below in Figure 8, the equilibrium balance results in one equation with two unknowns.



(a) (b)

Fig. 8 Slab method of analysis revealing; (a) element within a work piece (b) net external forces acting on the element [1]

The first equation (equation 5) is a balance of the horizontal forces acting on the element,

$$\left(\sigma_x + d\sigma_x\right)h + 2\mu\sigma_y dx - \sigma_x h = 0 \qquad (5)$$

where σ_x is the lateral stress distribution, σ_y the normal stress distribution, μ the coefficient of friction and h the height of the element.

Since the workpiece is subjected to triaxial compression, it is possible to obtain a second equation from the distortion-energy criterion for plane strain. The expression for this equation is:

$$\sigma_y - \sigma_x = \frac{2}{\sqrt{3}} Y = Y^I \qquad (6)$$

where Y^I is the yield stress in plain strain. Solving the above equations leads to

$$p = \sigma_y = Y' e^{2\mu(a-x)/h} \qquad (7)$$

where p is the extrusion pressure, h the height, μ the coefficient of friction and a the width of the slab at the boundary.

The slip-line field theory is another analytical method that has been used to determine extrusion pressure. It is generally applied to plane-strain conditions where the deforming body is assumed to be rigid, perfectly plastic and isotropic [1]. On the other hand the upper-bound solution, which is a derivative of "limit analysis", has been widely received and frequently applied. Here, the upper bound solution provides the value of power required to perform extrusion that is equal or greater than the actual power.

Limit analysis involves establishing the energy required to deform a work piece between a lower and upper bound. Although formulated by Prager and Hodge [10], this approach was advanced by Avitzur [8, 11] for metal working processes. In order to obtain exact solutions to metal working problems, it is necessary to adhere to a set of rules that satisfy prescribed conditions. These are [8]:

1. Satisfying the differential equations of equilibrium for the stress tensor throughout the deforming body.

$$\sigma_{ij,j} + F_j = 0 \qquad (8)$$

   where $\sigma_{ij,j}$ represents the stress component at a point and F_j the body force.

2. Maintaining continuity of flow i.e. volume of the body must be constant. This ensures that compatibility is satisfied by any strain or strain rate field obtained from an incompressible displacement or velocity field.

$$\varepsilon_{ij} = \frac{1}{2}\left[\frac{\partial U_i}{\partial X_j} + \frac{\partial U_j}{\partial X_i}\right] \quad (9)$$

where ε_{ij} is the strain tensor in cartesain coordinates, U the displacement vector and X the position vector.

3. The relationship between internal stresses and flow in the real material must be known and obeyed. A Von Mises material behavior is used to simplify these relationships, which are complex and not fully understood for real materials. As such, the Von Mises yield criterion is applied. This criterion assumes that flow of the work piece commences whenever the load applied is significantly large to initiate yield.

$$S_{ij} = \sigma_{ij} - \delta_{ij}S = \pm\frac{\sigma_o}{\sqrt{3}}\frac{\dot{\varepsilon}_{ij}}{\sqrt{\frac{1}{2}\dot{\varepsilon}_{kl}\,\dot{\varepsilon}_{kl}}} \quad (10)$$

where S_{ij} is the cartesian stress deviatoric tensor, ε_{ij}, ε_{kl} the strain rate components and σ_o the yield stress.

4. Geometric and static boundary conditions must be satisfied. This includes the friction behavior over the interface between the tool and work piece. The most common simplifying assumptions made for the friction stress, τ, are Coulomb friction, constant friction or hydrodynamic friction. Constant friction is most realistic for metal-forming processes. Constant friction assumes the shear stress, τ , is proportional to the strength of the work piece material i.e.

$$\tau = m\frac{\sigma}{\sqrt{3}} \quad (11)$$

where m is the shear factor and depends on the die, work piece and the type of lubricant.

A Von Mises material has the following properties [8]:

1. It is homogeneous
2. It is isotropic

3. Non-strain hardening
4. Does not undergo elastic deformations
5. Will flow indefinitely at constant load once flow is established
6. Strain rate insensitive

The upper bound on power, J*, is the sum of the following individual terms [8]:

$\dot{W}_i$ – Internal power of deformation $\frac{2}{\sqrt{3}}\sigma_o \int_v \sqrt{\frac{1}{2}\dot{\varepsilon}_{ij}\dot{\varepsilon}_{ij}}\, dV$ (12)

where dV is the change in volume

$\dot{W}_s$ – Shear power $\int_{S_v} \tau |\Delta V| dS$ (13)

where Δv is the change in velocity and dS the change in cross sectional area

$\dot{W}_b$ – Power to overcome opposing extrusion forces $-\int_{S_t} T_i v_i dS$ (14)

where T_i represents external stresses

$\dot{W}_k$ – Inertia forces $\frac{1}{2}\frac{\rho}{g}\int_{S_N} \dot{V}_i^3\, dS$ (15)

where ρ is the density of the material, g the gravitational acceleration and $\dot{V}$ the rate of volume change

$\dot{W}_p$ – Pore opening energy $\dot{V}.p$ (16)

where p is the hydrostatic component of stress

$\dot{W}_\gamma$ – Surface energy $\gamma \frac{ds}{dt}$ (17)

where γ is the energy rise with introduction of a unit of new surface energy and $\frac{ds}{dt}$ the rate of introduction of new surfaces.

For extrusion, it is safe to neglect the inertia forces, pore opening energy and surface energy. According to Prager & Hodge [10], the upper-bound theorem for extrusion then becomes:

$$J^* = \frac{2}{\sqrt{3}}\sigma_o \int_v \sqrt{\frac{1}{2}\dot{\varepsilon}ij\,\dot{\varepsilon}ij}\,dV + \int_{s_v} \tau\left|\Delta V\right| dS - \int_{s_t} T_i v_i dS \qquad (18)$$

By applying the above equation, Avitzur [11] derived the following solution for evaluating the extrusion stress for material flow through a conical converging die:

$$\frac{\sigma_{xb}}{\sigma_o} = \frac{\sigma_{xf}}{\sigma_o} - 2f(\alpha)Ln\left(\frac{R_o}{R_f}\right) - \frac{2}{\sqrt{3}}\left[\frac{\alpha}{Sin^2\alpha} - \cot\alpha + m(\cot\alpha)Ln\left(\frac{R_o}{R_f}\right) + m\left(\frac{L}{R_f}\right)\right] \qquad (19)$$

where α is the cone angle, m is the friction factor, L is the land/bearing length of the die, R_o the initial radius of the workpiece, R_f the final radius of the workpiece, σ_o the flow stress of the selected material, σ_{xb} is the back tension (compressive stress) and σ_{xf} the front tension. For an extrusion die there is a suitable cone angle, known as the optimal angle that minimizes the extrusion force. An approximate value of the angle (α_{opt}) can be computed by applying the following equation [11]:

$$\alpha_{opt} \approx \sqrt{\frac{3}{2} m \ln(R_o / R_f)} \qquad (20)$$

From the above equation, the optimal cone angle becomes smaller as the amount of area reduction is decreased. Also important to the design of the extrusion die is the die profile used. Although profiles such as straight converging die, sigmoidal dies and streamlined dies are possible solutions for achieving area reduction, the streamlined die has been proposed to be the optimum die profile [12, 13, 14]. Furthermore, Avitzur [11] proposes the use of a trumpet-shaped die similar to the one in Figure 9, if the die will be used for a wide range of reductions. This will enable processing of the workpiece at its optimal cone angle, which will minimize the required extrusion force. The equation describing the trumpet shape is [11]:

$$\frac{x}{R_f} = \frac{(R_o / R_f) - 1}{\tan\sqrt{\frac{3}{2} m \ln(R_o / R_f)}} \qquad (21)$$

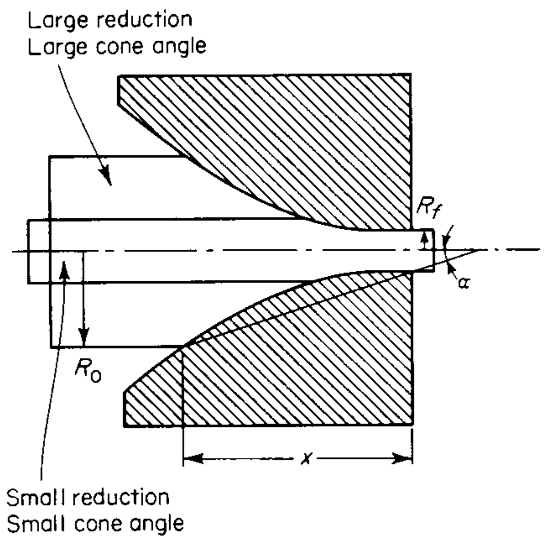


Fig. 9 Trumpet-shaped extrusion die-profile [11]

2.2.2 Buckling of compression members

The device (ram) that will transmit the force needed to deform the billet will be subjected to axial compression and as such can be treated as a "compression member". This implies that loads are applied along a longitudinal axis through the centroid of the member's cross section, thus enabling treatment of stresses as uniform across the cross section [15]. Bending may occur as a result of eccentricity of the load, but this is usually small and can be neglected in the analysis of the loads affecting the member. This enables us to treat the compression member as a column. Primary failure of the column can occur by compressive yielding of the material or by buckling. Buckling typically occurs at loads lower than the column's compressive strength. The load corresponding to the buckling limit is known as the critical buckling load and is a function of the column's slenderness. A typical column is shown below in Figure 10 with the possible transformation that may occur due to buckling.

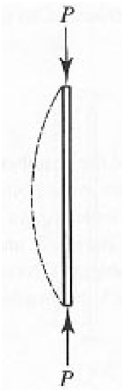


Fig. 10 Column under compressive loading with typical shape that may form as a result of buckling [15]

The critical buckling load, derived by Euler, is given by

$$P_{cr} = \frac{\pi^2 EI}{L^2} \tag{22}$$

where, P_{cr} is the critical buckling load, E is the material's elastic modulus, I is the moment of inertia of the cross-sectional area about the minor principal axis and L is the length of the column. A constant K, also referred to as the effective length factor, is included in the above equation to account for the possible end conditions of the column. As such, the corresponding Euler equation with the end-condition constant is:

$$P_{cr} = \frac{\pi^2 EI}{(KL)^2} \tag{23}$$

It is possible to obtain the critical buckling stress by further dividing the critical load by the cross sectional area. Using the moment of inertia relation $I = Ar^2$, the critical buckling stress can conveniently be expressed in the following form

$$\sigma_{cr} = \frac{P_{cr}}{A} = \frac{\pi^2 EAr^2}{A(KL)^2} = \frac{\pi^2 E}{\left(KL/r\right)^2} \tag{24}$$

where (L/r) in the above equation is known as the slenderness ratio of the column.

Typically for any material, the critical buckling stress is plotted as a function of the slenderness ratio (Euler buckling curve) and is used to describe the stability of any column constructed of the given material [15]. Since the stress at which buckling occurs may be greater than the proportional limit of the material, the graph of the critical buckling stress vs. the slenderness ratio is effectively divided into 2 regions, one being the region of elastic buckling and the other being the region of inelastic buckling. Figure 11 depicts the Euler buckling curve with the accompanying divisions into the elastic and inelastic buckling zones.

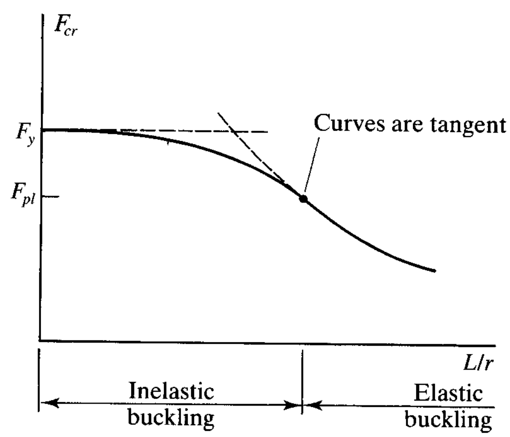


Fig. 11 Euler buckling curve showing division into regions of elastic and inelastic buckling [15]

In the elastic range of the curve, the critical buckling stress is determined according to equation 24. As for the inelastic range, the proportional limit is assumed to be at $F_y/2$, which enables the use of the following empirical formula [15]:

$$\sigma_{cr} = F_y \left[1 - \frac{(KL/r)^2}{2C_c^2} \right] \qquad (25)$$

where C_c is the value of KL/r corresponding to a stress of $F_y/2$ [15]. C_c is determined by setting the right side of equation 3 to $F_y/2$ thus resulting in:

$$C_c = \sqrt{\frac{2\pi^2 E}{F_y}} \tag{26}$$

Figure 12 displays the Euler buckling curve with the equations that describe both zones of division of the curve [15].

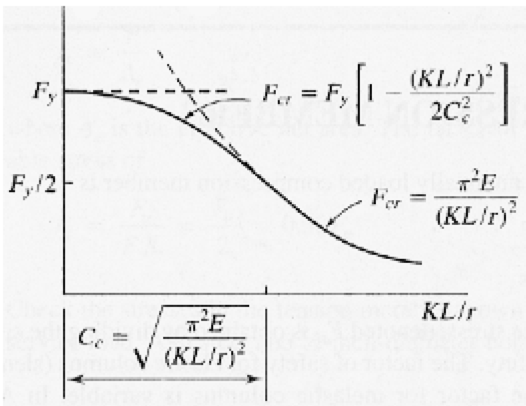


Fig. 12 Euler buckling curve with the equations for determining the critical buckling stress as a function of the column's slenderness ratio [15]

In order to design for allowable compressive stresses, factors of safety are incorporated into equations 24 and 25, by dividing the critical buckling stress by the appropriate safety factor. For the columns that behave in an elastic manner, the factor of safety applied is *23/12*, while for the inelastic columns the factor of safety applied is [15]:

$$\text{Factor of safety} = \frac{5}{3} + \frac{3(KL/r)}{8C_c} - \frac{(KL/r)^3}{8C_c^3} \tag{27}$$

Therefore, for slenderness ratios (KL/r) < C_c, the allowable stress can be computed with the following equation:

$$\sigma_{allowable} = \frac{F_y\left[1 - \frac{(KL/r)^2}{2C_c^2}\right]}{\frac{5}{3} + \frac{3(KL/r)}{8C_c} - \frac{(KL/r)^3}{8C_c^3}} \quad (28)$$

Also, for slenderness ratios > C_c, the allowable stress is:

$$\sigma_{allowable} = \frac{12\pi^2 E}{23(KL/r)^2} \quad (29)$$

2.3 *Design Methodology*

As previously mentioned within the introduction section, the classical design methodology will be applied to generate a simple practical design for implementing the extrusion tool. The classical design methodology uses a top-bottom approach and includes the following elements in some form or another [16]:

1. An upstream stage that involves identification and analysis of a need prior to conceptual design.
2. A conceptual design stage to create new ideas that satisfy the need.
3. A downstream stage that involves the design and development of the concept into an overall product or system layout.

The process starts with the identification of a need statement followed by the definition of functions that must be provided by the system. The system's requirements (functional and requirements) are determined next after defining the need and functions. Following this, the conceptual design and detailed design are then implemented. The flow of the design process recognizes that the interface between each step of the process is bidirectional. Hence a conceptual design can be sent back to the function structure phase for refinement if the design overlooks issues that may have been brought up within the need statement and analysis.

The need statement creates a clear definition of the problem at hand. The need analysis then serves as a process of transforming the often vague statement of the design task into a set of design requirements [16]. As such, the need analysis assists the designer to develop substantial insight into the functions of the system. The function structure, which is typically extensive, serves as a basis for decomposing the system into subsystems based on the functions that each must provide. This is accomplished primarily by using functional flow diagrams and a functional analysis. The functional flow diagram is developed primarily to structure the system requirements in functional terms, illustrate series and parallel relationships as well as to portray the hierarchy of system functions and functional interfaces [17]. The functional requirements are the lowest level of decomposition of the function structure that serves as a baseline for generating the system's performance requirements.

As for the system's performance requirements, they quantify how well the functional requirements must be done. The system's requirements need to be precise in definition and must be verifiable in order to assist with the design evaluation and possible selection of alternatives [16]. Also, the costs and schedule of the design process are driven to a large part by the design requirements. The conceptual design involves generating and implementing the fundamental ideas that characterize a product or system [16]. During this stage, the designer generates several concepts that are evaluated against each other with criteria to determine, which one will be developed further. It is typically an iterative process and is sometimes referred to as a feasibility study. Refinement of the system requirements may be done before or after a concept has been selected.

Following the conceptual design process is the preliminary design, which is sometimes referred to as embodiment design. During this phase, a structured development of the design concept takes place [18]. This phase is concerned with three major tasks – product architecture, configuration design and parametric design [18]. During this stage decisions are made on strength, material selection, manufacturing processes, shape, size and spatial compatibility of the system and its components. Detail design proceeds after completion of the preliminary design. Here the design is brought to the stage of a complete engineering description of a tested and producible product [18].

At this stage, each component is fully described in terms of the form, dimensions, tolerances, surface properties, materials and manufacturing processes [18]. Solid models and detailed engineering drawings are generated to aid manufacturing of each part. In addition, assembly drawings and instructions for assembly and disassembly of the system's components are prepared as well. After completing all the aforementioned tasks, a design review is performed before passing on the information to the manufacturer.

3. DESIGN CONCEPT AND CONFIGURATIONS

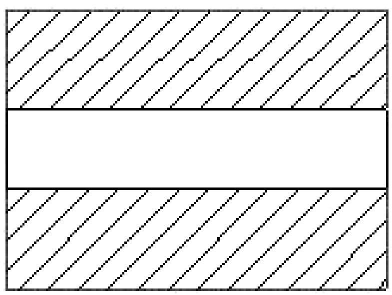
3.1 *Tooling Concepts and Associated Benefits*

The basic form of the area reduction extrusion die developed in this project is an assembly of several components. The major components include a chamber containing the workpiece, a ram that will transfer the compressive force to push the material to flow from the inlet channel to the outlet channel and a die that possesses the shape that will determine the final form of the workpiece. Some of the different configurations that exist for components of the area reduction extrusion tool include:

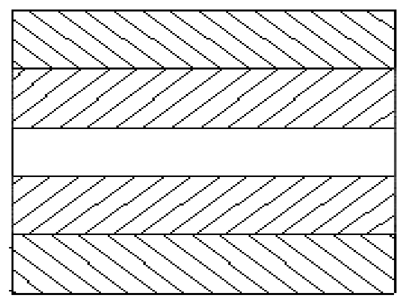
1. Monobloc vs. compound containers
2. Die Profiles such as flat faced, straight converging or curved dies
3. Fixed or replaceable die assembly

<u>Monobloc vs. compound containers</u>: The container is the outer portion of the tooling assembly that surrounds the channel where the work piece is inserted. During extrusion, radial forces act on the container as tangential and radial stresses, which can be very high [19]. The container can be designed out of a single component (monobloc container) or several components (compound container). For monobloc containers, there is no inner liner/core. A single wall, which is the combination of the core and outer wall, is all that exists. Compound containers are composed of several components and typically have a liner/core in addition to the outer wall. Depending on the type of application that is required, compound containers are more suitable whenever high service loads are anticipated. This is because high stresses typically concentrate on the inner wall of monobloc containers during extrusion and this restricts the load carrying capacity of the container. Compound containers have an advantage over monobloc containers because the inner liner/core can be induced with compressive residual stresses by shrink-fitting into the outer wall. Whenever tensile stresses arise due to the extrusion pressure, the residual compressive stresses within the material must be overcome before tensile stresses are formed. As such, proper determination of compressive residual

stresses makes it possible for pre-stressed compound containers to sustain higher stresses than monobloc containers [19]. Another advantage of compound containers over monobloc containers is that different grades of steel can be used for the individual sections based on the relevant thermal and mechanical stress profiles developed while in service [19]. The inner liner/core, which sustains higher loads and wear, can be made of better grades of steel than the outer wall (container) of the tool. Schematic illustration of monobloc and two-piece compound containers are presented in Figure 13.



(a)



(b)

Fig. 13 (a) Monobloc container and (b) Two-piece compound container

<u>Die profile</u>: The die profile that is used in implementing the area reduction extrusion tool is another important factor to be considered in the design process. This is because the die profile affects the load and stresses that are formed in the tool during the forward extrusion process. Some of the profiles that are possible are flat-faced dies, straight converging dies and curved wall dies as illustrated in figure 13. Previously mentioned within the theory section, streamlined dies have an optimum profile when compared to flat-faced and straight converging dies. Maity et al. and Tyne et al. show that straight converging dies provide the least upper bound extrusion pressure under high friction conditions [20, 21]. Also, curved dies are more expensive to manufacture than flat-faced dies or straight converging dies. Furthermore, any of the aforementioned die profiles can be designed as multistage dies. Multi-stage dies are typically double reduction dies

where the second reduction stage has a reduction in area less than 2%. Multi-stage dies are designed to aid the extrusion of brittle materials, which are predisposed to surface cracks that arise from longitudinal or circumferential residual stresses [7]. It is believed that the low second reduction stage prevents cracking by imposing an annular counter pressure on the work piece as it exits the first portion of the die [7]. Typical die profiles are shown in Figure 14.

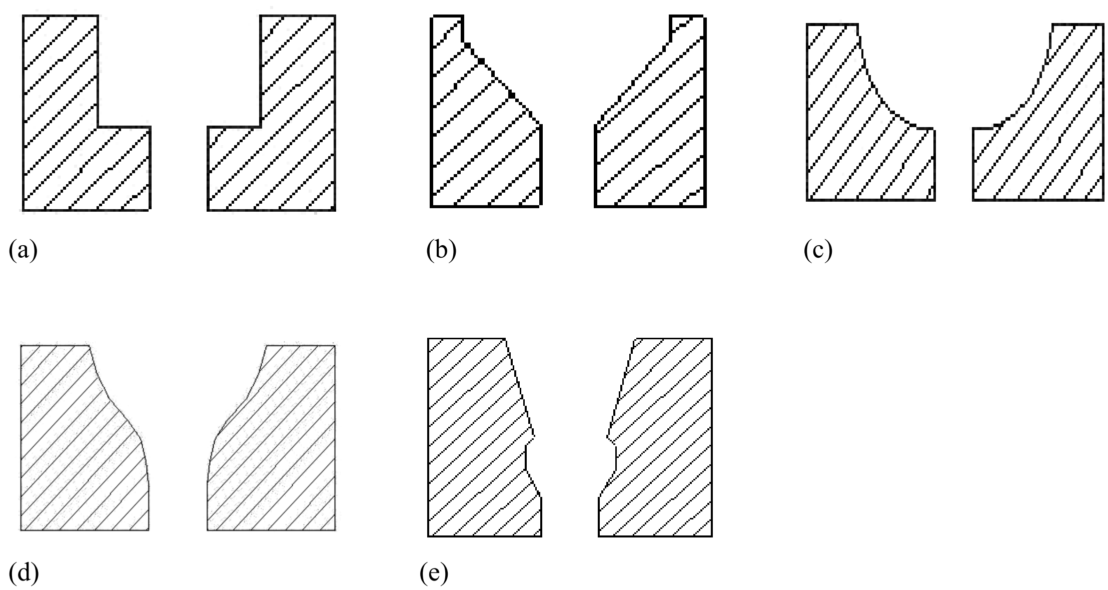


Fig. 14 Typical die profiles showing a (a) flat-faced die, (b) straight converging die, (c) curved surface die, (d) streamlined die and a (e) multi-stage die

<u>Fixed vs. replaceable dies</u>: Wear is an important factor that affects the life of an area reduction extrusion tool. Consequently, the proper design of the die takes on added significance. The die can be designed as a separate assembly from the tool or it can be incorporated into the container design. Inserts made of appropriate wear resistant material can be used for the entire die or zone of the die exposed to wear action. The die can then be replaced after its designated service life.

3.1.1 Performance requirements

The performance requirements to be satisfied by any proposed design of the area reduction extrusion tool are specified below in Table 3.

Table 3 Functional requirements and associated performance requirements of tool design

Functional Requirements	**Performance Requirements**
Provide means to reduce the number of machining processes	Extrusion type that is used should be able to process (reshape) work piece to desired size in a single pass
Provide means to interface/connect area reduction extrusion tool with ECAE tool	Shape and size of area reduction extrusion tool should fit within a 3 meter radial zone around the ECAE tool
Provide means to accommodate ECAE deformed billets before reshaping	Inlet channel of the area reduction extrusion channel must have a square cross section that is greater than 1.06 in. by 1.06 in
Provide means to accommodate billet after reshaping	Outlet channel of the tool must have a square cross section of 0.98 in. by 0.98 in., the desired size of the processed billet
Provide means to interface with power source	The ram, which is connected to power source must be able to sustain a pressure greater than 113,000 psi; the upper limit of flow stress to be processed by the extrusion tool
Provide means to constrain deformation of billet	Material to be used for tool construction must be capable of supporting 113, 000 psi; the upper limit of flow stress to be processed by the extrusion tool

Table 3 Continued

Functional Requirements	**Performance Requirements**
Provide means to interface with billet	The ram must have the same shape as the work piece and fit easily into the inlet channel of the area reduction extrusion tool
Provide means to transfer force to billet	A die profile with a square cross section and inlet specification of than 1.06 in by 1.06 in and outlet specification of 0.98 in by 0.98 in must be used
Provide means to straighten edges of billet upon undergoing area reduction	Incorporate land with cross section of 0.98 in. by 0.98 in. Land length must be greater than one-half of material width

Based on the tool configurations and performance requirements that have been identified, three conceptual designs will be proposed to serve as the basis for the development of the final area reduction extrusion tool. The first concept (Concept I) is a tool with the following major configurations:

1. Monobloc container
2. Flat faced die
3. Fixed die
4. Single stage reduction die
5. Ram with constant cross section

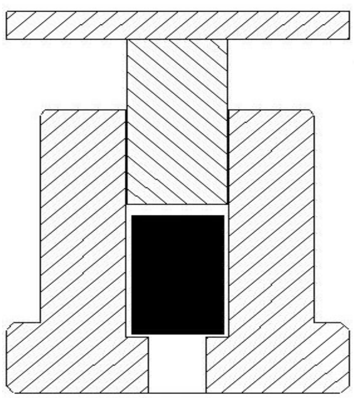
The second concept (Concept II) has the following major configurations:

1. Two-piece compound container with split inner liner
2. Straight converging die
3. Replaceable die assembly
4. Single stage reduction die
5. Ram with variable cross section

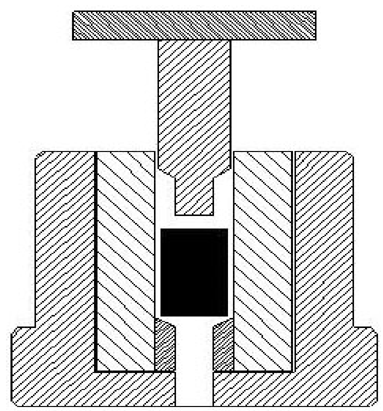
The third concept (Concept III) has the following configurations:

1. Three-piece compound container with split inner liner
2. Curved die profile
3. Replaceable die assembly
4. Multi-stage reduction die
5. Ram with variable cross section

A schematic of each concept described above is presented in Figure 15:



(a)



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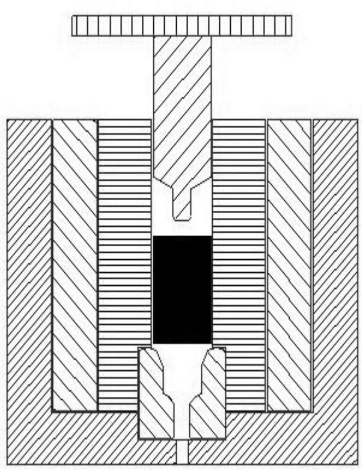


(c)

Fig. 15 Conceptual designs of area reduction extrusion tool showing (a) Concept I (b) Concept II (c) Concept III

3.1.2 Tool selection criteria

A list of tool selection criteria, which uses a down select process is established for the comparison of the alternative designs in order to select the conceptual design that will be further refined within the preliminary and detailed design phases. The elements of the criteria and their definition are:

1. Manufacturability
2. Assembly and disassembly of tool
3. Cost
4. Materials
5. Component & tool life
6. Surface finishing and machining requirement
7. Required extrusion pressure

<u>Manufacturability:</u> All components in the system should be easily fabricated using existing methods and processes such as turning and cutting. If a component in the system requires a difficult manufacturing process, then the overall cost of the system would be increased unnecessarily.

<u>Assembly and disassembly of tool:</u> The selected tool should be one that can be easily assembled and disassembled if there is a need to replace any worn or damaged system component or billets that are stuck. This is a very important criterion since the extrusion process is one that involves significant frictional contact between the work piece and the tool, which often leads to sticking of the work piece to the tool's wall whenever there is inadequate lubrication.

<u>Cost:</u> The cost of operating the area reduction extrusion tool and integrating with the existing ECAE tool should be less than the present machining (rolling and milling) costs.

Materials: The components of the system should be constructed using only readily available materials, preferably steels. If non-metals, expensive materials or alloys are used, the overall cost of the system will increase unnecessarily.

Component and tool life: The die, which is the tool component of the tool that is subjected to significant loads, should be able to sustain at least 500 cycles before any replacement/servicing is warranted. Other components of the area reduction extrusion tool should operate without failure or the need for servicing for a period not less than five years.

Surface finishing and machining requirement: Whenever a component is expected to support a load during service, the design should avoid any sharp corners that tend to act as stress raisers. In addition, the material selected for construction of the tool should be easily machined and must not require expensive surface finishing in order to be used in its final form.

Required extrusion pressure: The concept that is selected should optimize or reduce the extrusion pressure needed to force the work piece through the die. By lowering the extrusion pressure, it is possible to select less exotic materials that will reduce the overall cost of building the tool.

Now that the criteria are established and defined, the next step is assigning a rank and weight to each element. This is achieved through the use of a binary dominance matrix. This matrix is shown in Table 4.

Table 4 Binary dominance matrix for criteria ranking

		A	B	C	D	E	F	G	H	Total	Rank
A	Manufacturability	X	0	0	0	0	0	0	1	1	7
B	Assembly and disassembly of tool	1	X	1	1	1	1	0	1	6	2
C	Cost	1	0	X	0	1	0	0	1	3	5
D	Materials	1	0	1	X	1	1	0	1	5	3
E	Component and tool life	1	0	0	0	X	0	0	1	2	6
F	Surface finishing & machining	1	0	1	0	1	X	0	1	4	4
G	Required extrusion pressure	1	1	1	1	1	1	X	1	7	1
H	Dummy variable	0	0	0	0	0	0	0	X	0	

This matrix was set-up in the following way:

1. Each of the criteria is listed along the left side as well as the top.
2. Each row is considered in turn.
3. At each position a simple question is asked "Which criterion is more important than the other? For example: In the "D column" of the Cost row, the question asked would be "Is Cost more important to the design than Materials?" In this case the answer would be "No!" Therefore a '0' would be placed in the position. A '1' would be placed in the position for a Yes answer. This process continues until all positions are filled.
4. The Total column is then filled in by summing up all numbers in that row.
5. The rank of the criteria is determined by the number in the Total column for that criterion. The highest number was ranked first and so on.

A weight factor is determined from the binary dominance matrix by dividing the total from each row by the total number of allocated points. The results of this process are shown in Table 5.

Table 5 Criteria ranking and weighting

	Criteria	Total	Rank	Weighting
G	Required extrusion pressure	7	1	0.250
B	Assembly & disassembly of tool	6	2	0.214
D	Materials	5	3	0.179
F	Surface finishing & machining requirement	4	4	0.143
C	Cost	3	5	0.107
E	Component and tool life	2	6	0.071
A	Manufacturability	1	7	0.036
H	Dummy Variable	0	8	0.000
		28		1.000

With this procedure complete the next step in the down select process is to construct a down select matrix. The purpose of this matrix is to compare each of the concepts with respect to each criterion. This matrix is constructed as follows:

1. Each concept is rated from 0 to 1, 1 being the highest, as to how well it satisfied that specific criterion. The ratings for all three concepts must add up to 1 for each criterion.
2. These ratings are then multiplied by the weighting for that criterion.
3. The numbers found in step two are then summed up to determine which concept best satisfies the criteria of the design.

The down select matrix is shown in Table 6, where Concept 2 emerges as the concept that best satisfies the criteria. Also, it can be seen that while Concepts 1 and 3 are very different, their final weightings were not too far apart. Since the down select process depends on the individual's judgment, another individual may analyze each weighting criterion differently against the three concepts presented thus leading to a possible selection of Concepts 1 or 3. The possibility of variable results is accounted for by considering down-select tables completed by other competent individuals with tool design experience. The results are combined together with the values from Table 6 to obtain average weightings of each concept. Table 7 presents an average down-select matrix, which includes input from four individuals. Once again, Concept 2 emerges as the top concept, while Concepts 1 and 3 have ranks that are reversed from their positions in Table 6.

Table 6 Author's down-select matrix

	Extrusion Pressure	Assembly & disassembly of tool	Materials	Surface finishing & mchining	Cost	Components and tool life	Manufacturability	Overall Percentage %
Weighting factor	25	21.4	17.9	14.3	10.7	7.1	3.6	100
Concept 1	0.2	0.48	0.33	0.2	0.13	0.2	0.25	27.75
Concept 2	0.55	0.3	0.34	0.36	0.38	0.45	0.35	39.93
Concept 3	0.25	0.22	0.33	0.44	0.49	0.35	0.4	32.33
	1	1	1	1	1	1	1	

Table 7 Average down-select matrix from four individuals

	Extrusion Pressure	Assembly & disassembly of tool	Materials	Surface finishing & mchining	Cost	Components and tool life	Manufacturability	Overall Percentage %
Weighting factor	25	21.4	17.9	14.3	10.7	7.1	3.6	100
Concept 1	0.18	0.46	0.345	0.3	0.4	0.24	0.428	32.4
Concept 2	0.4	0.34	0.345	0.34	0.34	0.35	0.361	35.74
Concept 3	0.41	0.2	0.311	0.36	0.26	0.41	0.212	31.86
	1	1	1	1	1	1	1	

3.2 *Selected Tool Configuration*

The tool concept that was selected for further development tool is composed of seven major components. Standard parts such as bolts will be used in addition to these seven components. In addition, there will be multiples of some of the major components. The seven major components of the tool are displayed in Figure 16.

ITEM NO.	PART NUMBER	QTY.
1	Base Plate	1
2	Punch Plate	1
3	Wedge (Inner Liner)	4
4	Container	1
5	Ram	1
6	Die Insert	4
7	Flange Lock	4

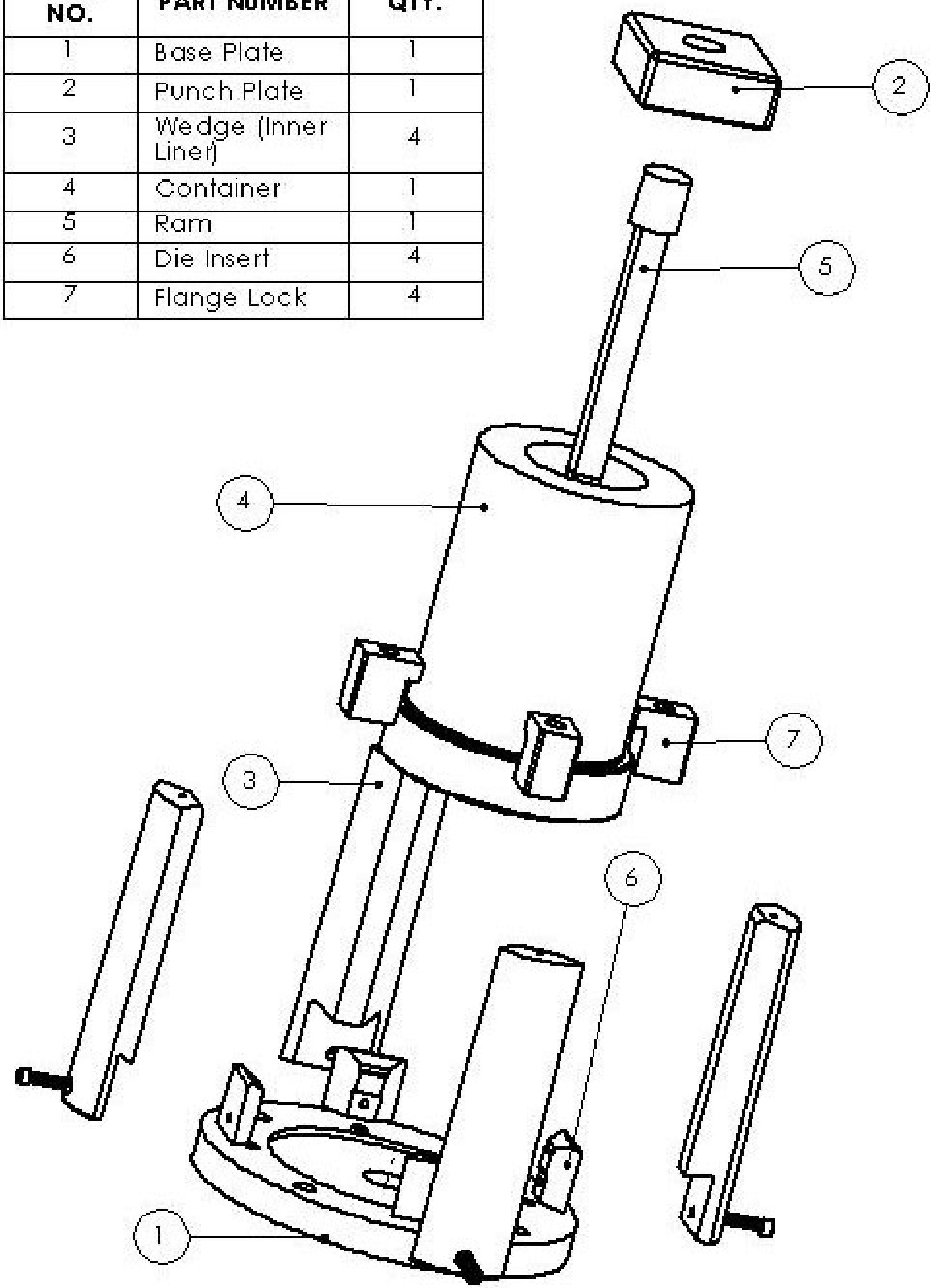


Fig. 16 Exploded view of selected tool assembly

The above components are combined together to form a simple tool assembly that minimizes the use of redundant components. The punch and punch plate form an assembly that is used to transmit the force needed to sustain flow of the work piece from the inlet channel into the outlet channel. Die inserts, which are replaceable, are used to mitigate the problem of tool damage that may arise over prolonged exposure of the deformation surface to the various kinds of materials that the tool will process. Each one of the 4 die-insert forms an assembly with the corresponding wedge (liner). The wedges are then combined within the container to form the inlet and outlet channel of the tool. Four flange locks and 5/8-inch bolts are used to secure the container assembly to the base plate. The internal wall of the container has a slight taper that matches the taper on the wedges. This will assist in assembling the liner within the container. In addition, the internal diameter of the container will be slightly smaller than that of the liner (assembled wedges) in order to create an interference fit between these components.

3.3 *Assembly of Area Reduction Extrusion Tool*

The assembly of the area reduction extrusion tool will be achieved by putting together sub-assemblies initially and then combining the sub-assemblies afterwards. This can be done as a 3-stage process. The first stage involves putting together the following sub-assemblies:

1. Punch and punch plate
2. Wedges and die inserts

For the punch and punch plate, this is achieved by screwing the punch into the internal threads created within the punch plate. Each die insert is then attached to the corresponding wedge with the use of a single 3/8-inch bolt. The second stage of the assembly process involves putting together the wedge and die insert assembly into the container of the area reduction extrusion tool. This is accomplished with the use of a press, which is used to force the wedges simultaneously into the container through the bottom opening. By simultaneously forcing all the wedges into the container, an interference fit is created between the wedges and the inner wall of the container since the diameter formed by the wedges is slightly larger than the inner diameter of the container. The final stage of the assembly process involves combining the container assembly with the punch assembly and also a base plate. This is achieved by placing the container assembly into the groove created within the base plate and then vertically restraining it with the use of 4 equally spaced flanged locks that are fastened to the base plate with 5/8-inch hexagonal bolts. Following this, the assembly is then aligned beneath the punch assembly, which is connected to a power supply.

3.4 *Material Selection and Assessment*

Material selection for extrusion dies is paramount to the design of long-lasting dies with minimal performance related issues. It is anticipated that the area reduction tool will process a wide range of materials. As such, material selection must incorporate secondary issues such as surface finishing, applicable heat treatments and material fabrication after dealing with the primary issue of the extrusion pressure. Some of the requirements that must be satisfied by a material that will be used for an extrusion tool include [22]:

1. Be machinable by basic processes such as cutting and eroding
2. Possess good resistance to pressure, temperature and wear
3. High strength and toughness
4. Adequate surface hardness
5. Ability to be polished to a satisfactory finish on non porous surfaces
6. Respond adequately to simple heat treatment
7. Undergo minimal distortion and little changes to the dimension during any heat treatment
8. Good resistance to corrosion from chemicals
9. Good thermal conductivity
10. Ability to undergo surface treatment such as plating and nitriding

Steels are typically selected as the material of choice for most extrusion dies, although certain non-ferrous materials are occasionally used. The steels that will be selected for constructing the area reduction extrusion tool can be classified according to their composition. As such, classes of steel such as carbon, low-alloy and tool steels are potential categories from which material selection will be made.

Carbon steels are steels that do not have specifications for minimum content of any possible alloying elements. They are generally categorized according to carbon content. Table 8 shows each of the possible division of carbon steels based on the amount of carbon present within the steel. Low-alloy steels, which are the second class of steels mentioned, constitute a category of ferrous materials, which exhibit mechanical properties superior to plain carbon steels as a result of the presence of alloying elements [23]. These alloying elements such as nickel, chromium and molybdenum can range from fractions of a percent up to the levels in stainless steels, which have a minimum of 10% chromium. Low-alloy steels can be classified into the following major groups [23]:

1. Low-carbon quenched and tempered steels
2. Medium-carbon ultrahigh-strength steels
3. Bearing steels
4. Heat-resistant chromium and molybdenum steels

Table 8 Categories of carbon steels

Category of Carbon Steels	Low-carbon steels	Medium-carbon steels	High-carbon steels	Ultra-high carbon steels
Chemical composition (% carbon content)	0.30 (max)	0.30 – 0.60	0.60 – 1.00	1.25 – 2.00

Low-carbon quenched and tempered steels are often utilized whenever the possibility exists that heat treatment would lead to material distortion and changes in the dimension. The steels are annealed (tempered) to improve toughness. The annealing process lowers the strength and hardness of the steel and this can be mitigated by surface treatment of the steels afterward. Medium-carbon ultrahigh-strength steels are structural steels with very high strength levels that can exceed 1380 MPa (200 ksi). Bearing steels are steels that are easily machined and possess good wear resistance with high hardness after undergoing heat treatment or case hardening. In addition, these steels have a low carbon content that is less than 0.2 wt. % and can be enriched by carburization. Finally, chromium and molybdenum heat-resistant steels are designed for improved oxidation and corrosion resistance as well as improved strength at elevated temperatures. These steels typically contain chromium within a range of 0.5% to 9% and molybdenum within a range of 0.5% to 1%.

Tool steels are another class of steels that are used to cut, form and shape a material into a useful form or part [22]. Tool steels typically contain medium to high amounts of alloying elements that make it possible to meet severe service demands as well as the ability to be heat treated without large distortion and crack formation. Similar to low-alloy steels, the composition of tool steels on the basis of carbon content creates a situation of overlap. As such, a readily acceptable categorization of tool steels based on machining applications will be applied. The different categories of tool steels are presented in Table 9 with specific examples of each type.

Table 9 Categories of tool steels based on machining applications

Tool steel classification	AISI letter symbols	Typical Examples
High-speed tool steels	M , T	M1, M2, T1, T2
Hot-work tool steels	H	H10, H12, H13
Cold-work tool steels	D, A, O	D2, D3, A2, O6
Shock-resisting tool steels	S	S1, S2, S7
Mold tool steels	P	P2, P5, P20
Special-purpose tool steels	L	L2, L6
Water-hardening tool steels	W	W1, W2

High-speed tool steels are developed for use in high-speed cutting applications [23]. Hot-work tool steels are designed to withstand the effects of heat, pressure and abrasion associated with plastic deformation processes that are performed at high temperatures. On the other hand, cold-work tool steels are restricted in application to processes that do not involve prolonged or repeated heating that is above 205°C to 260°C (400°F – 500°F) [23]. Shock-resisting steels are those that combine high strength, high toughness and moderate wear resistance. These steels have manganese, silicon, chromium, tungsten and molybdenum as the principal alloying elements. Unlike shock-resisting steels, special purpose tool steels also known as group L steels contain small amounts of the alloying elements found in shocking-resisting steels. Mold steels contain chromium and nickel as principal alloying elements. Finally, water-hardening steels have carbon as the principal alloying element. These steels typically have small amounts of chromium and vanadium, which increase hardenability and enhance toughness.

Based on the classification provided, the selection of steels to be used in the design and construction of the extrusion tool will depend on anticipated operating conditions. As such, parts/components that will sustain severe service loads will be designed with the appropriate tool steels, while those components that sustain low to moderate loads will be designed with carbon and low alloy steels. Often, the parts that will sustain severe loads are in direct contact with the work piece. Table 10 displays each component of the tool excluding standard parts such as bolts and the nature of the anticipated service loads. The punch is expected to sustain high compressive loads without yielding or buckling, while the container is expected to sustain tensile loads in the form of hoop stresses as a result of the radial loads transmitted by the deforming work piece. The die insert (liner) should be pre-stressed in compression when it is assembled within the container. In addition, the wedge and die inserts are expected to sustain high compressive and perhaps shear forces resulting from the deformation of the work piece. Furthermore, the base plate is expected to support the weight of the entire tool assembly while the flange lock restrains any vertical motion that might occur during operation of the tool. Finally, the punch plate is expected to sustain the weight of the punch and be used to guide the lateral translation of the punch once it has been withdrawn from the tool.

Table 10 Anticipated service conditions of individual components of extrusion tool

Component of area reduction extrusion tool	Expected service loads
Punch	High loads
Container	Moderate loads
Base plate	Moderate loads
Wedge (liner)	High loads
Die insert	High loads
Punch plate	Moderate loads
Flange lock	Moderate loads

Material selection for each tool component will be determined by the applicable selection criteria, which ranks relevant factors affecting the performance of each tool component. The criteria for each component are specified in Table 11 in order of the most important factor to the least important factor:

Table 11 Material selection criteria for tool components

Tool Material	**Material Selection Criteria**
Punch	Ability to sustain high cyclic compressive loads, high modulus of elasticity, high resistance to shock loading, good resistance to upsetting (rigidity), deep hardenability, cost
Container	Tensile loads (fatigue stresses), crack resistant (good fracture toughness), ability to be heat treated, cost
Base Plate	Compressive strength, low toughness, cost
Punch Plate	Tensile strength, cost
Die Insert	Resistance to wear and shock loading, high toughness, deep hardenability
Wedge (Liner)	Ability to be pre-stressed, wear resistance, high temperature strength, cost, deep hardenability
Flange Lock	Toughness

From the criteria established above, the material selection of each component of the tool is based on the categories of steel categories previously discussed. The steel category and materials selected for use are presented within Table 12.

Table 12 Materials selected for various tool components

Tool Component	Category of Steel	Material
Punch	Shock resisting tool steel	S7 tool steel
Container	Medium-carbon ultrahigh-strength steel	304 Stainless steel
Base plate	Low carbon steel	AISI 4140
Wedge (liner)	Shock resisting tool steel	S7 tool steel
Die Insert	Shock resisting tool steel	S7 tool steel
Punch Plate	Medium-carbon ultrahigh-strength steel	AISI 4140
Flange lock	Low carbon steel	AISI 4140

4. ENGINEERING ANALYSIS AND DESIGN ISSUES

4.1 In-Service Loads and Associated Displacements

A successful tool design is one that has been designed to accommodate the various loading conditions possible and incorporates that into the concept chosen in order to achieve optimal performance. Each component of the tool experiences some form of loading during the operation of the tool. The severity of loading that is applied to each component is dependent on the service condition as highlighted previously within Table 10. As a compression member, the punch is susceptible to buckling as a result of its aspect ratio and the compressive loads that it will transmit during the extrusion process. In addition, it is susceptible to fatigue effects due to the dynamic loading that it experiences. At the same time, the punch experiences lateral elastic deformation due to Poisson's effect during loading and this should be accounted for within its design. The container is expected to sustain tensile loads arising from the outward pressure exerted by the deforming billet. The tensile loads act in the form of a hoop stress within the container walls. In addition the container should be able to restrict the outward motion of the liners/inner wedges, which are pressed into the container. The liner/inner wedges are expected to restrain lateral deformation of the billet prior to the start of area reduction. The base plate is designed to support the full loading during extrusion, while the punch plate serves to connect the ram to its hydraulic power supply. As for the die insert, it is expected to support shear and compressive loads exerted by the billet during sliding and area reduction and transmit the load outwards to the liner and container. A summary of the questions and issues to be addressed within this section to ensure a feasible and practical tool design are:

1. Produce engineering drawings of the tool's components, assembly and relevant sections. Discuss tolerance to be incorporated; required heat treatments and surface finish for critical components.
2. Evaluation of the upper bound extrusion force required to process various materials through the tool.
3. Evaluate the buckling limits of the tool's punch (ram) and plot the critical load as a function of the slenderness ratio. In addition, consider the effects of different column end conditions on the buckling limit of the punch.
4. Evaluate the lateral expansion of the punch during operation of the tool to predict any possible interference with the walls of the channel.
5. Evaluate the stresses and corresponding deformation (hoop, radial) within the wall of the container assembly that are required to constrain the billet, with the application of appropriate safety factors.
6. Consider the effects of the land length and width on the geometry and the exit dimension of the reshaped billet.

4.1.1 Solid model, engineering drawings and sections of tool assembly

The assembled extrusion tool is displayed as figure 17, while engineering drawings of the major tool components, tool fabrication mounts and sections are presented in figures 18 through 31.

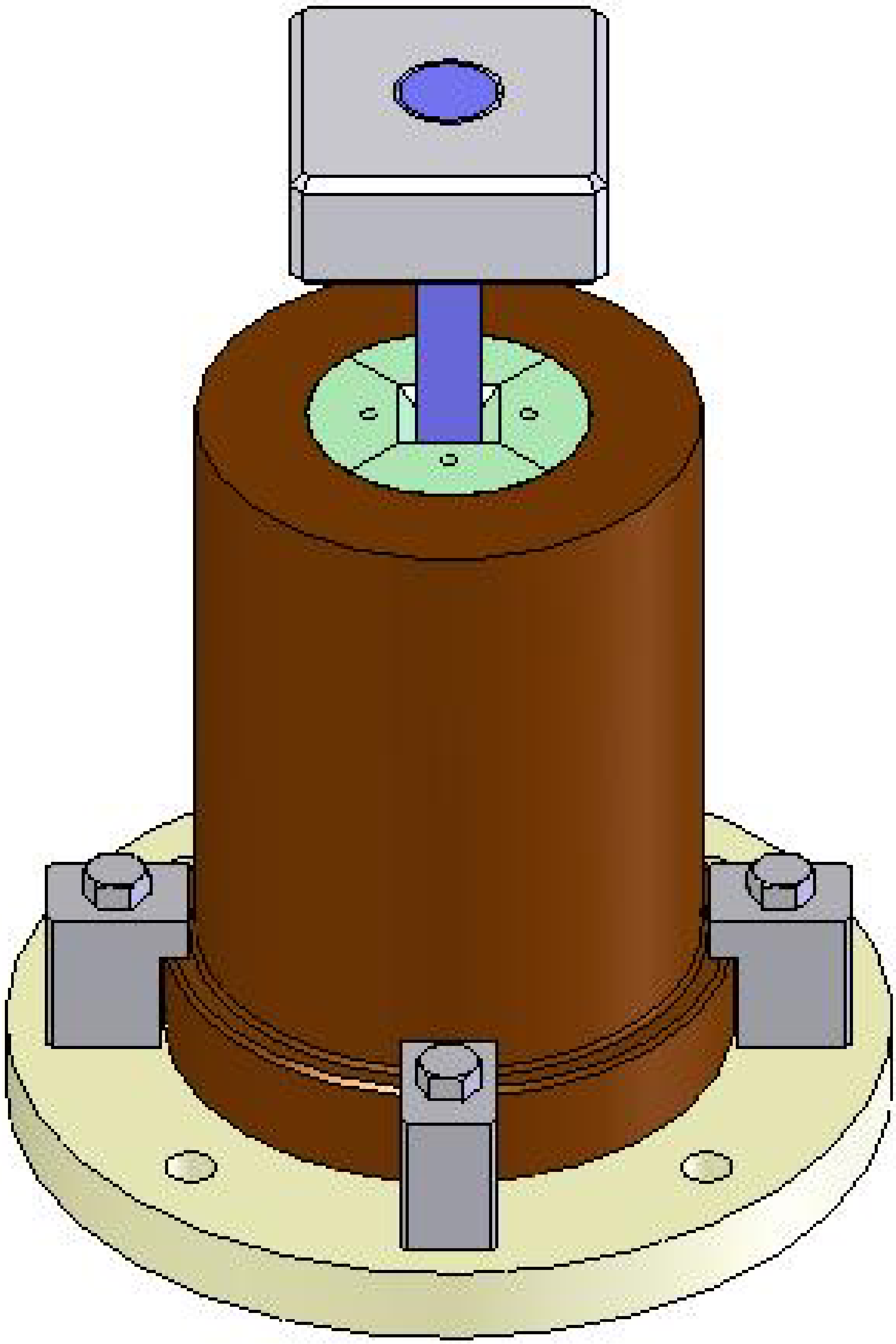


Fig. 17 Assembly of area reduction extrusion tool

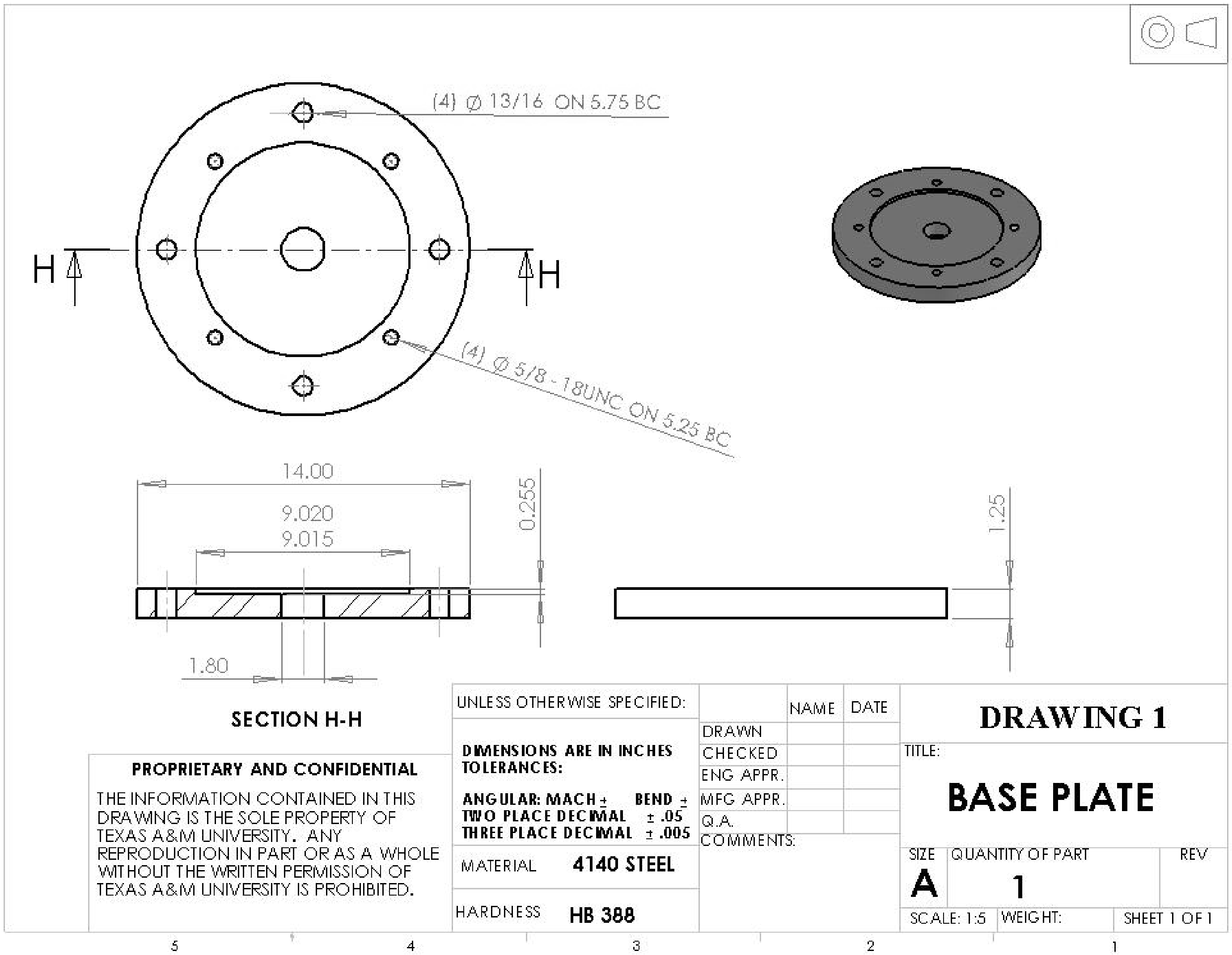


Fig. 18 Tool component - Base plate

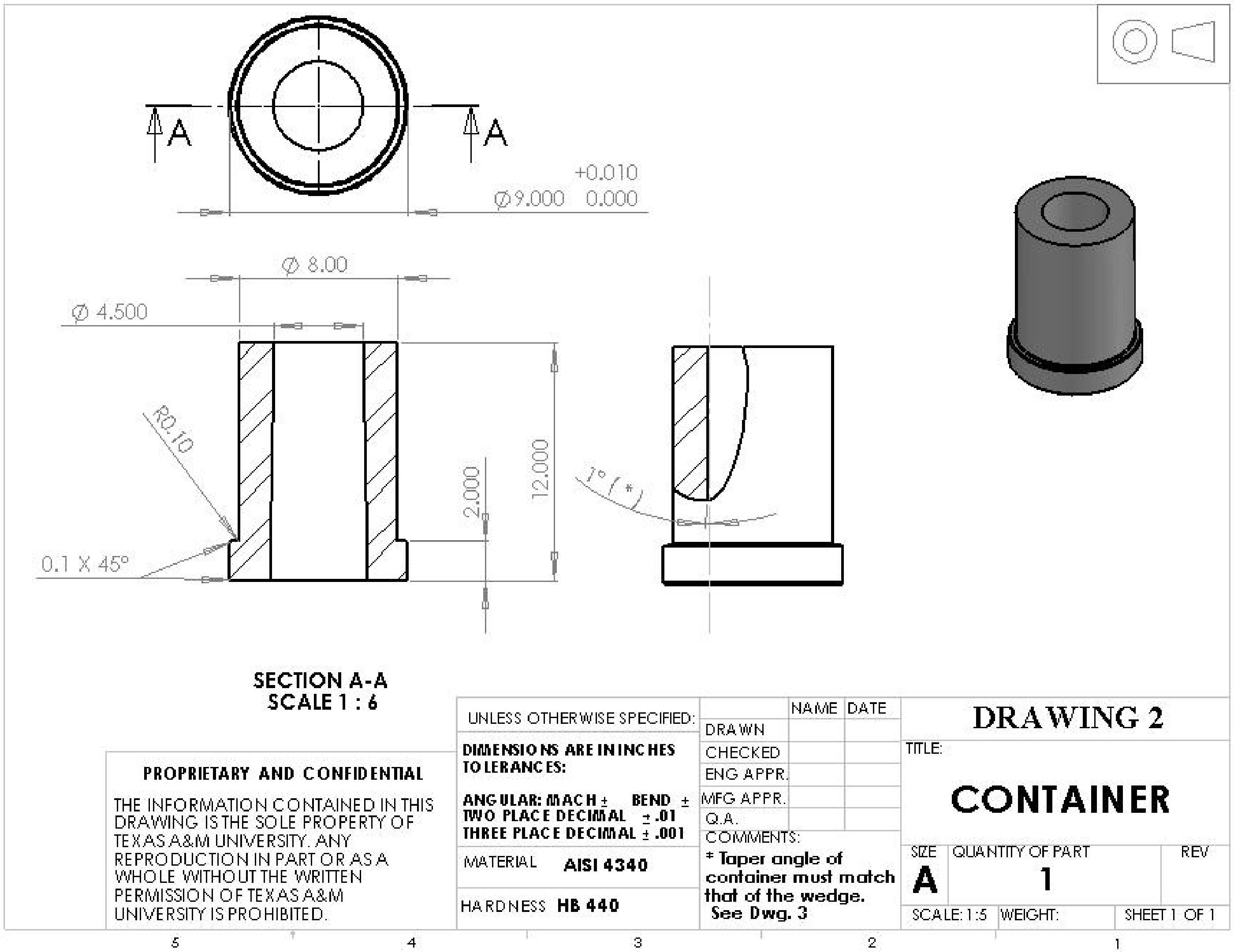


Fig. 19 Tool component - Container

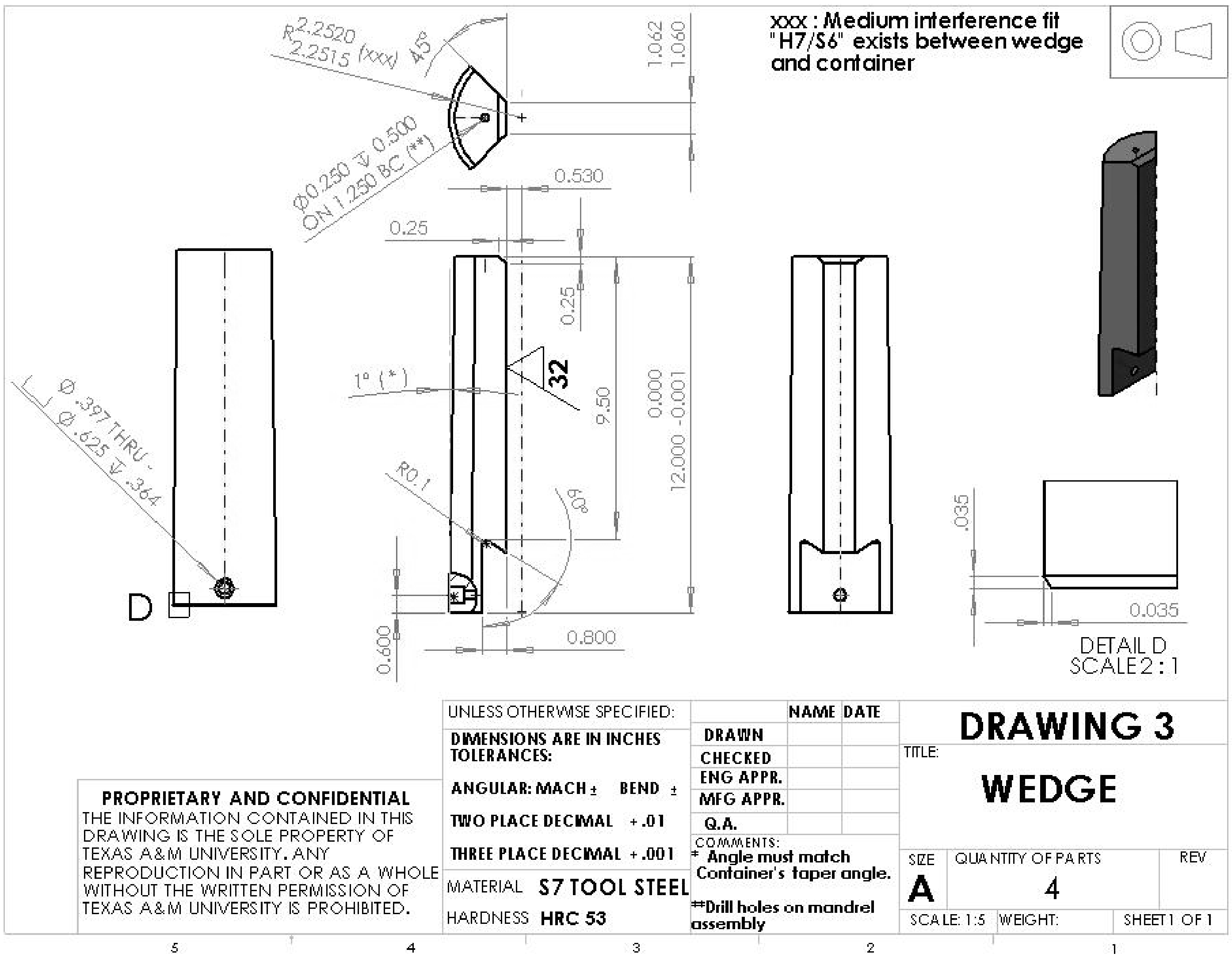


Fig. 20 **Tool component - Wedge**

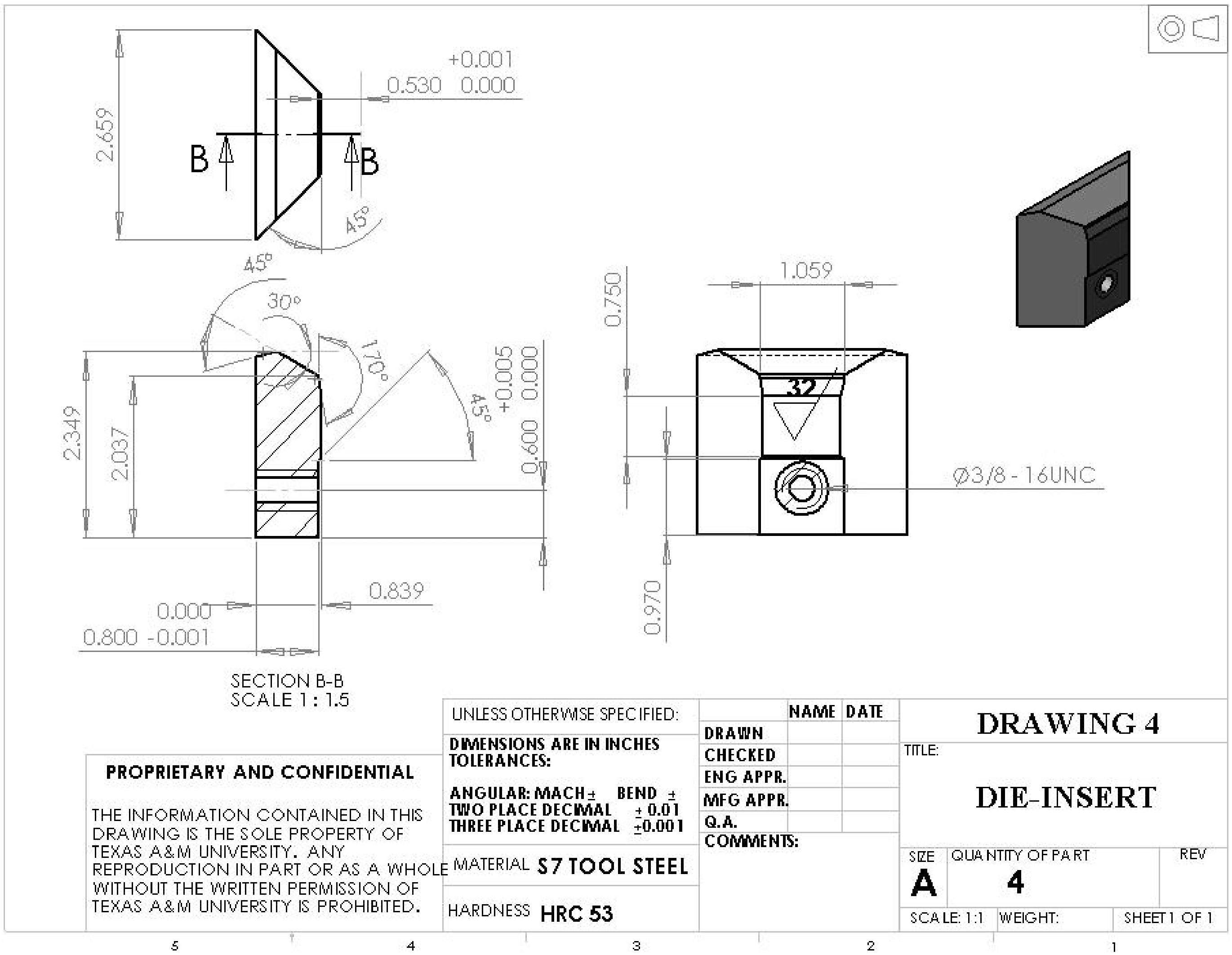


Fig. 21 Tool component - Die insert

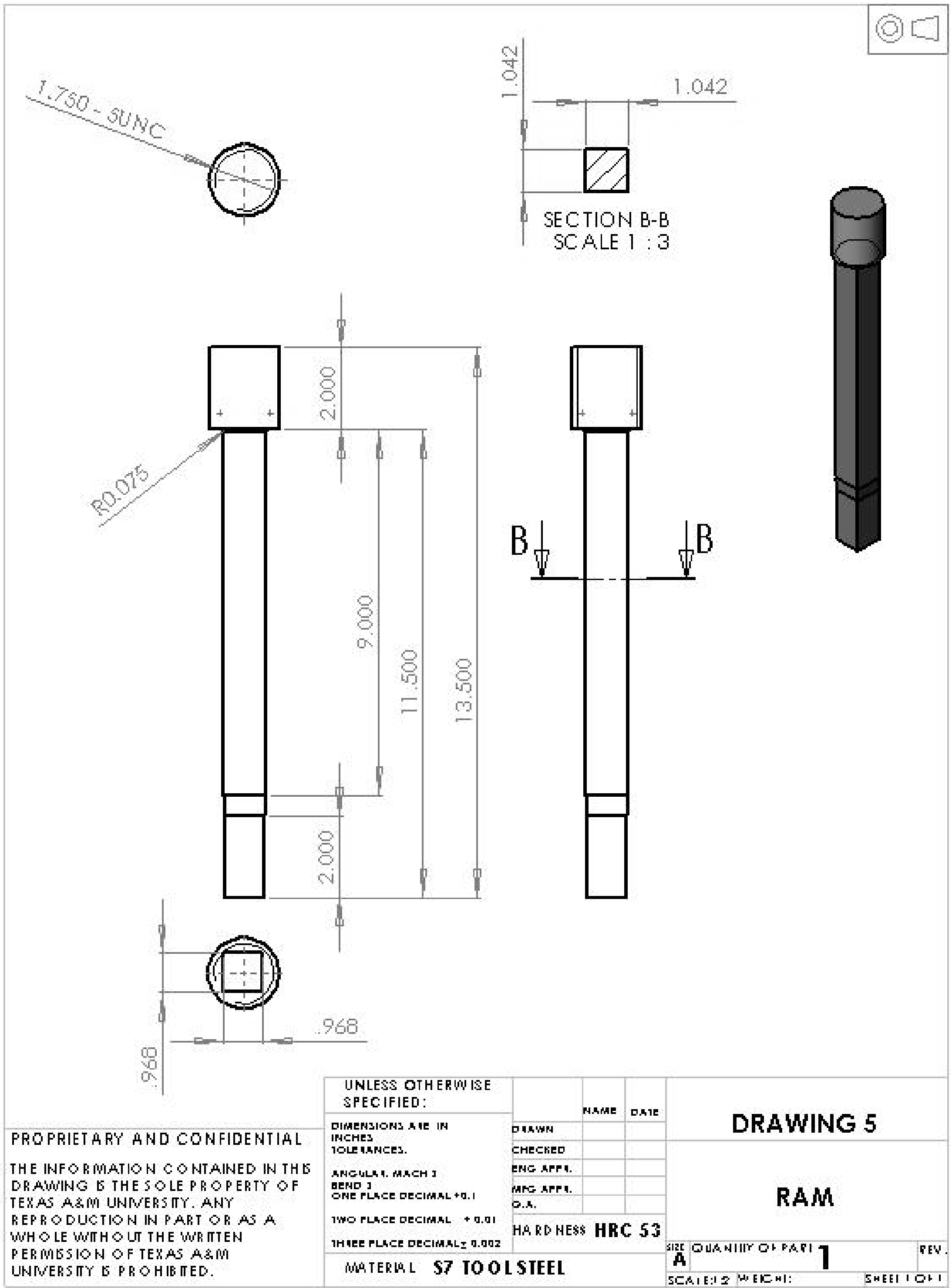


Fig. 22 Tool component - Ram

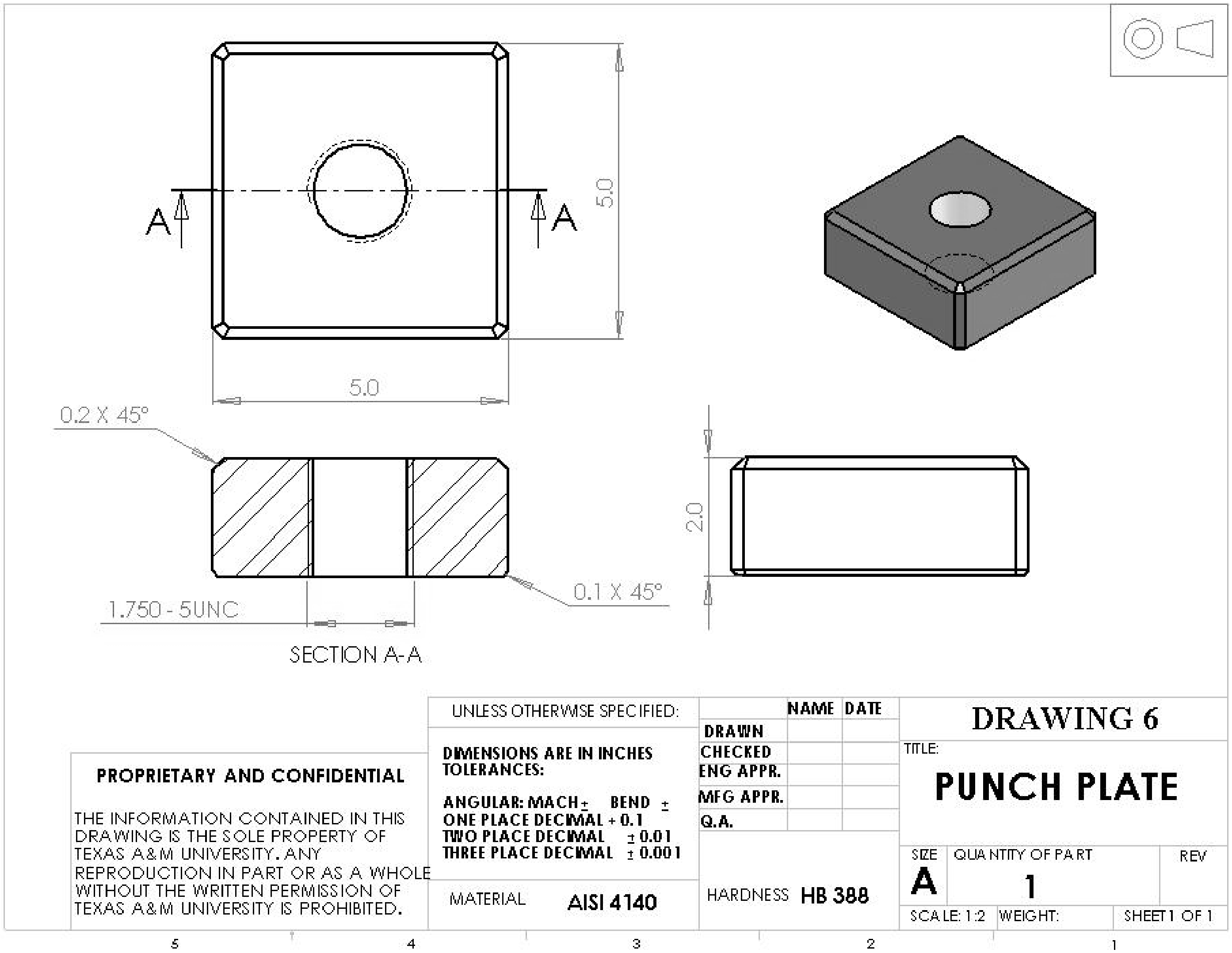


Fig. 23 **Tool component - Punch plate**

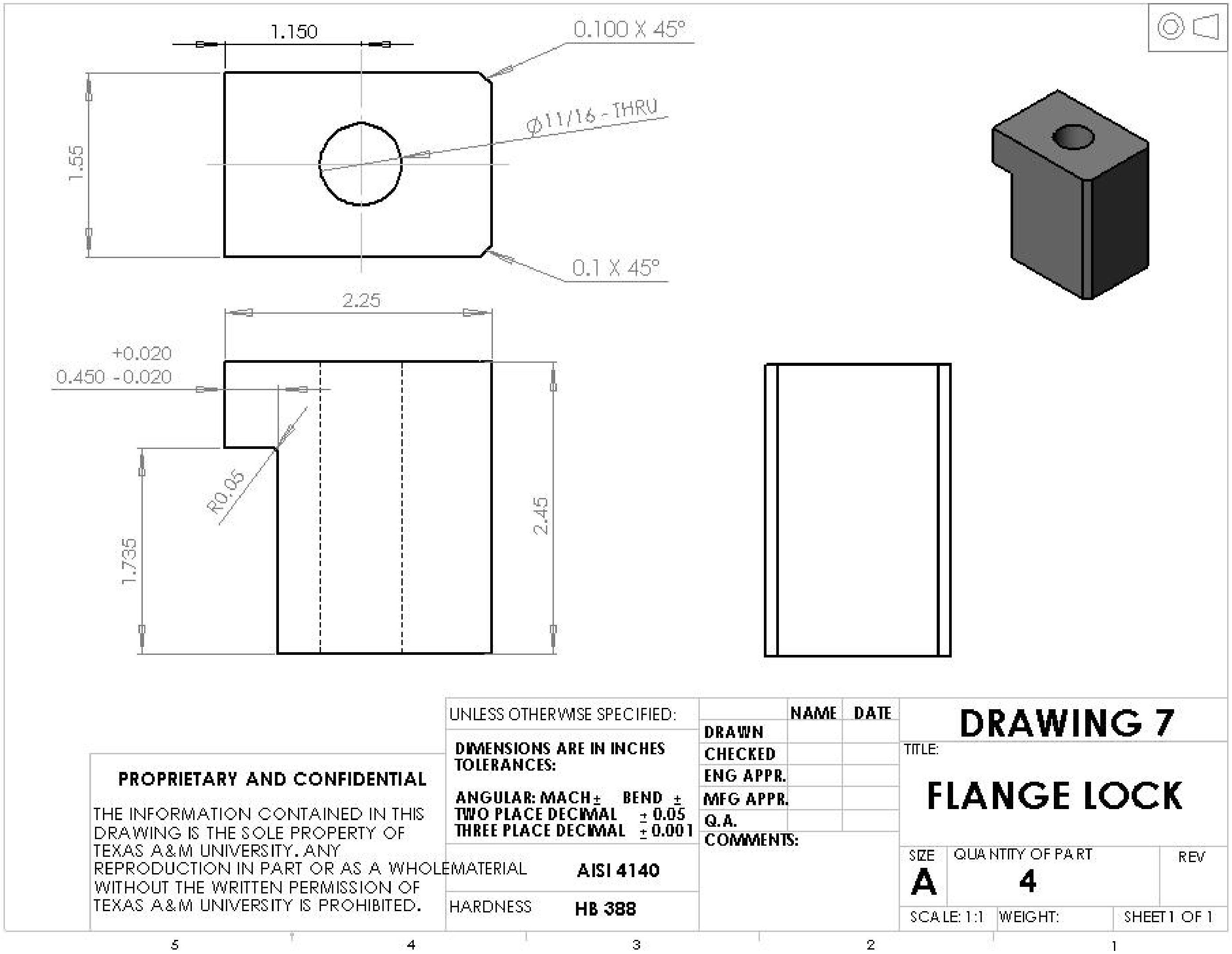
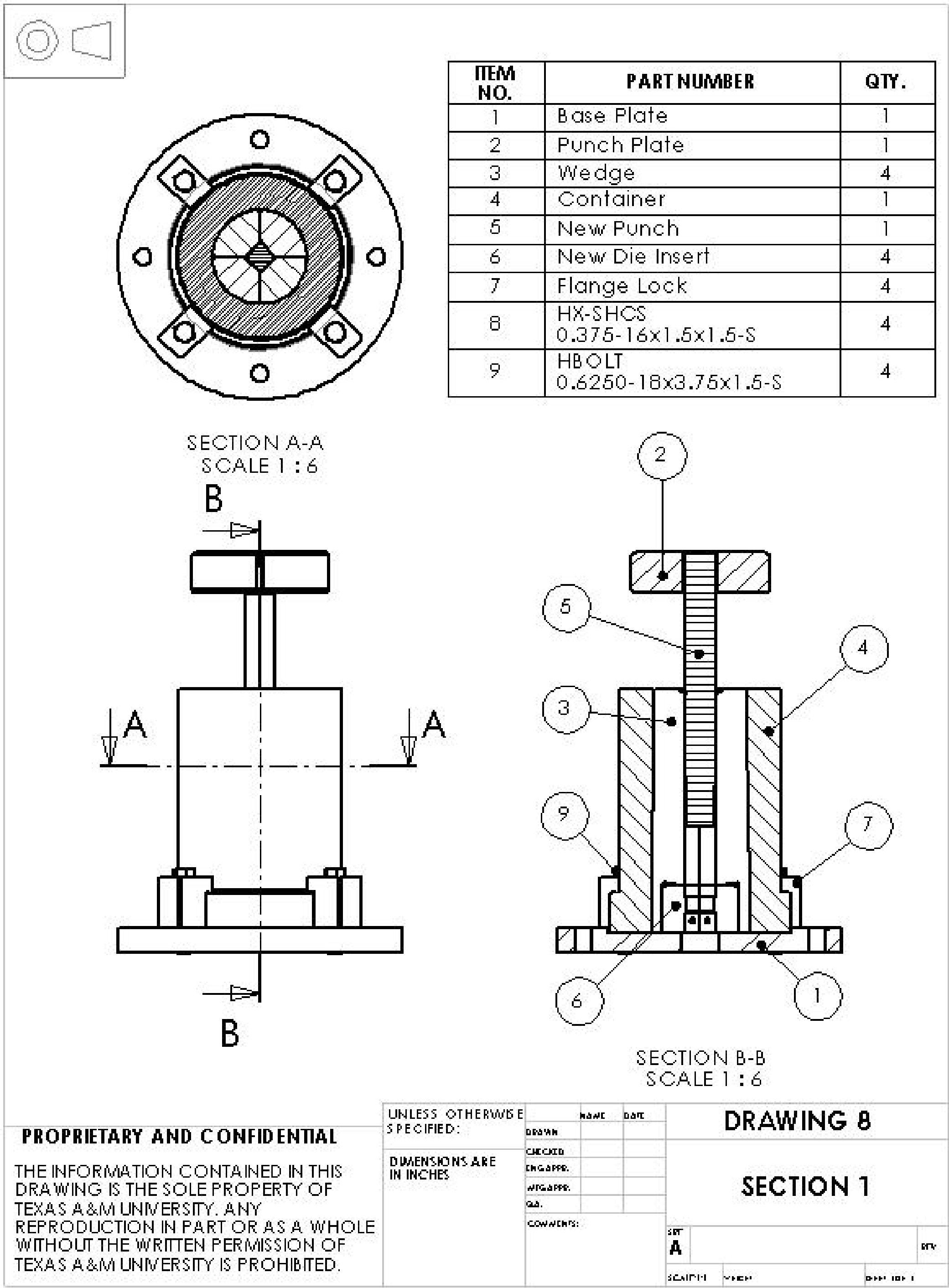


Fig. 24 Tool component - Flange lock



ITEM NO.	PART NUMBER	QTY.
1	Base Plate	1
2	Punch Plate	1
3	Wedge	4
4	Container	1
5	New Punch	1
6	New Die Insert	4
7	Flange Lock	4
8	HX-SHCS 0.375-16x1.5x1.5-S	4
9	HBOLT 0.6250-18x3.75x1.5-S	4

Fig. 25 Section through assembly of area reduction extrusion tool

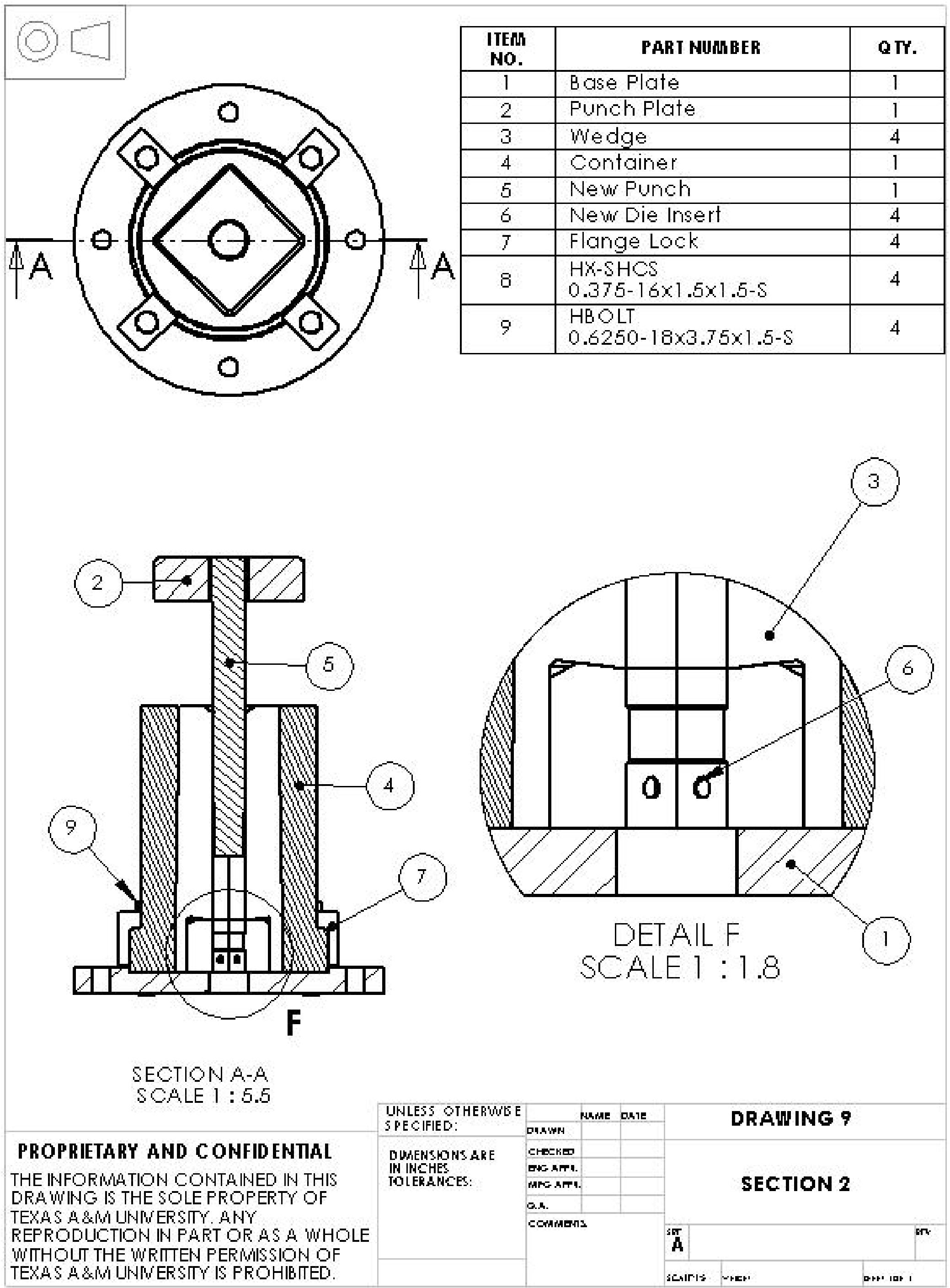
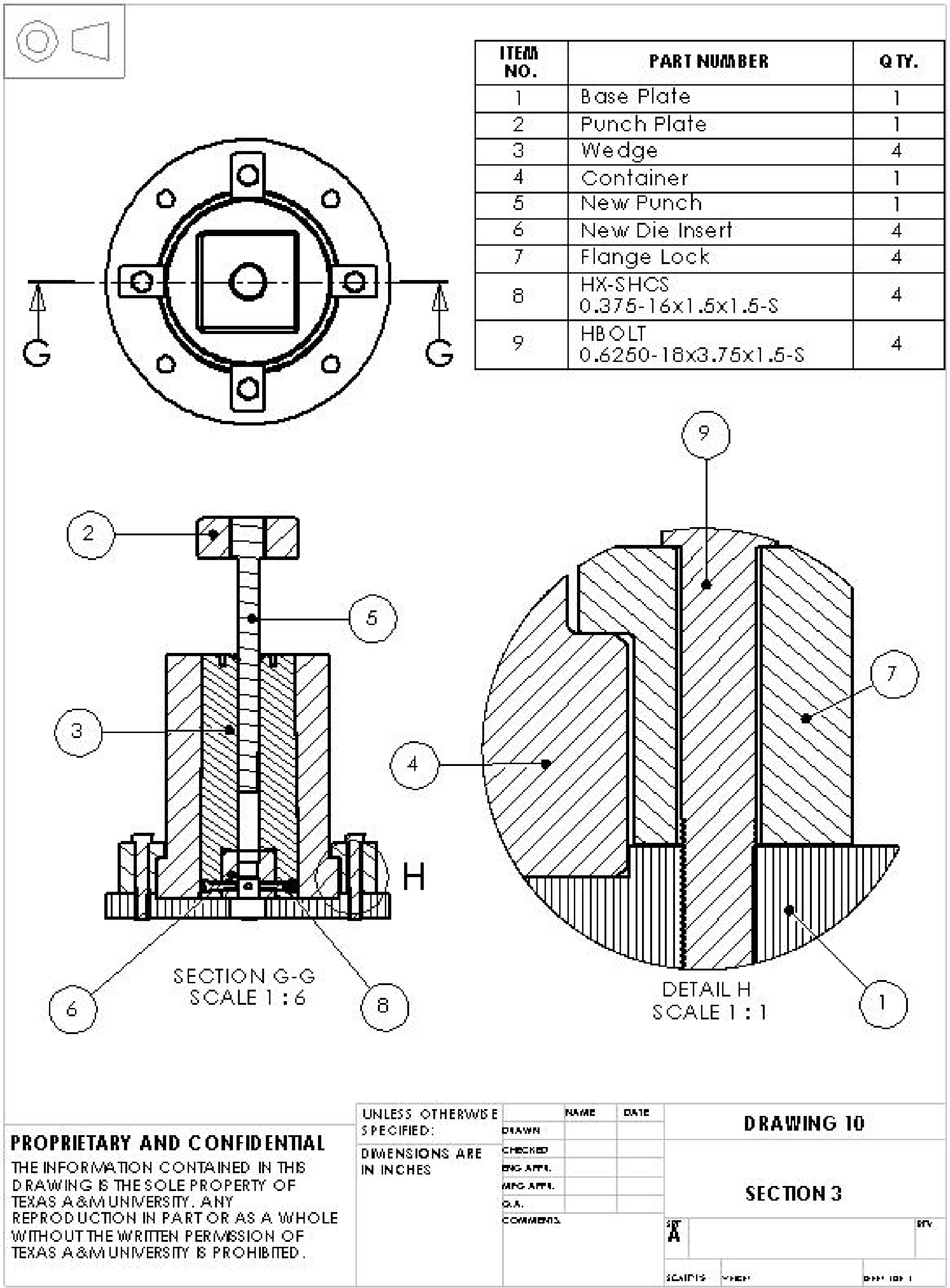


Fig. 26 **Section through area reduction extrusion tool showing details of the die insert sub-assembly**



ITEM NO.	PART NUMBER	QTY.
1	Base Plate	1
2	Punch Plate	1
3	Wedge	4
4	Container	1
5	New Punch	1
6	New Die Insert	4
7	Flange Lock	4
8	HX-SHCS 0.375-16x1.5x1.5-S	4
9	HBOLT 0.6250-18x3.75x1.5-S	4

Fig. 27 Section through area reduction extrusion tool showing details of the flange lock sub assembly

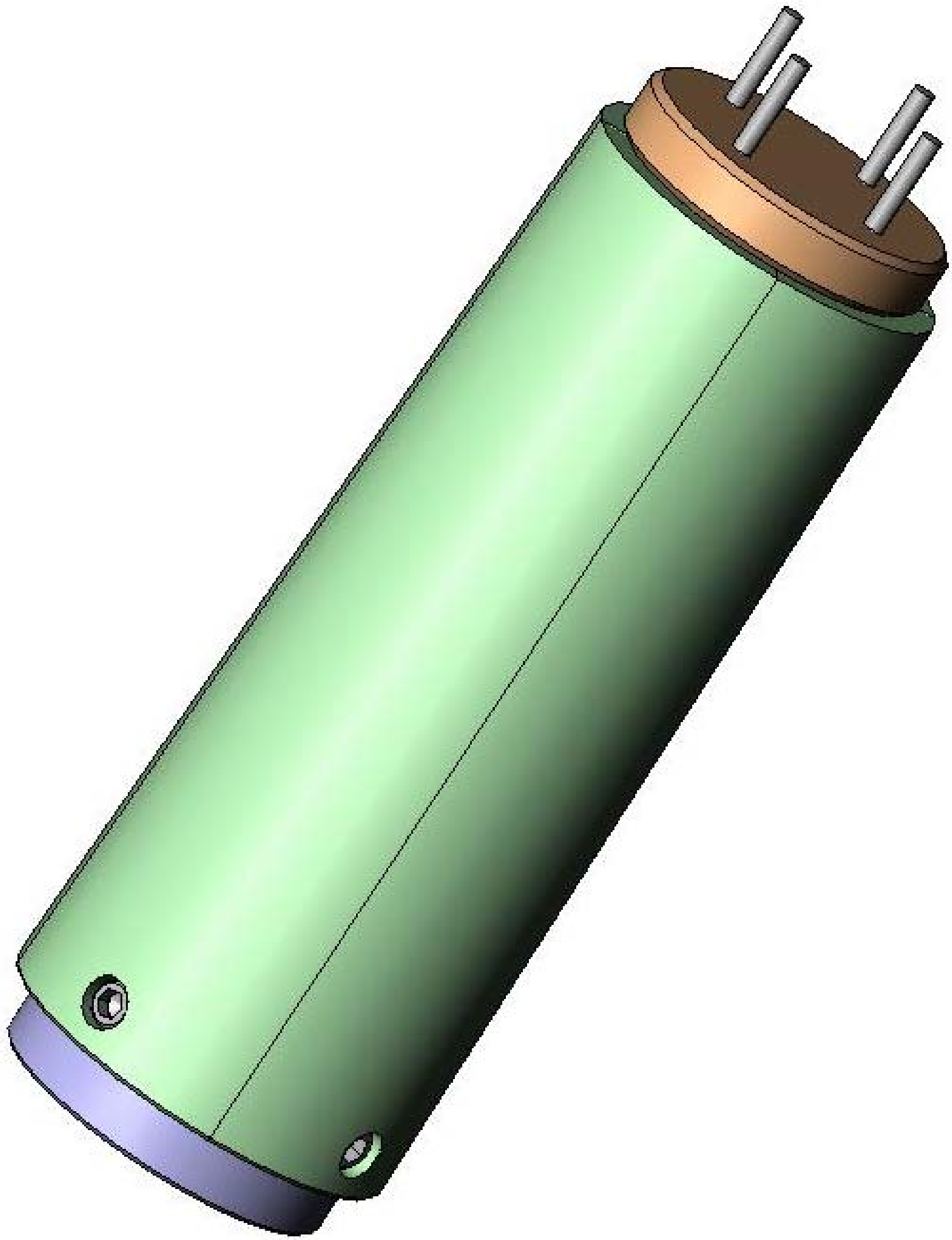


Fig. 28 Assembly of individual wedges mounted on turning support

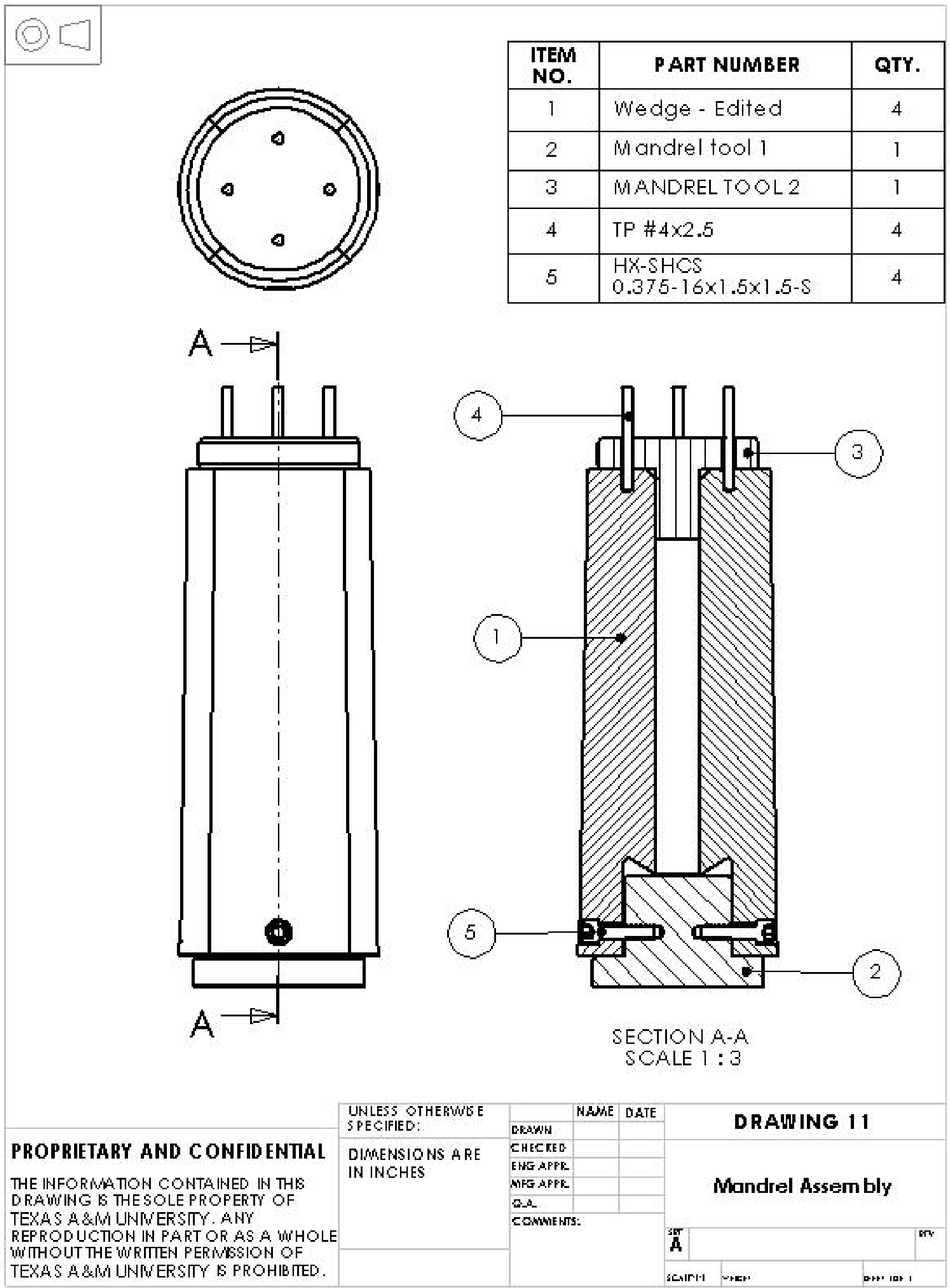


Fig. 29 Section through assembly of individual wedges mounted on turning support

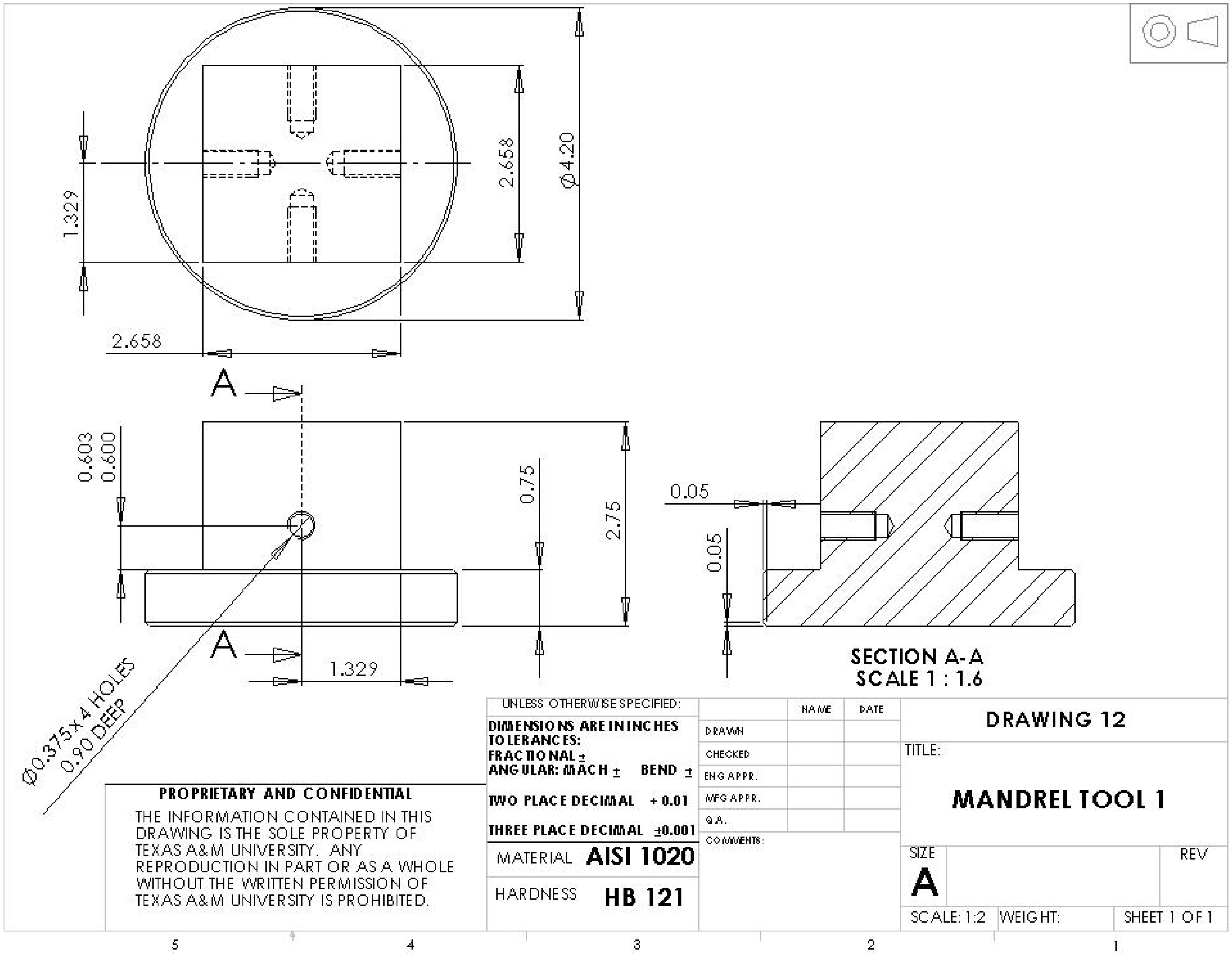


Fig. 30 **Mandrel tool for securing individual wedges**

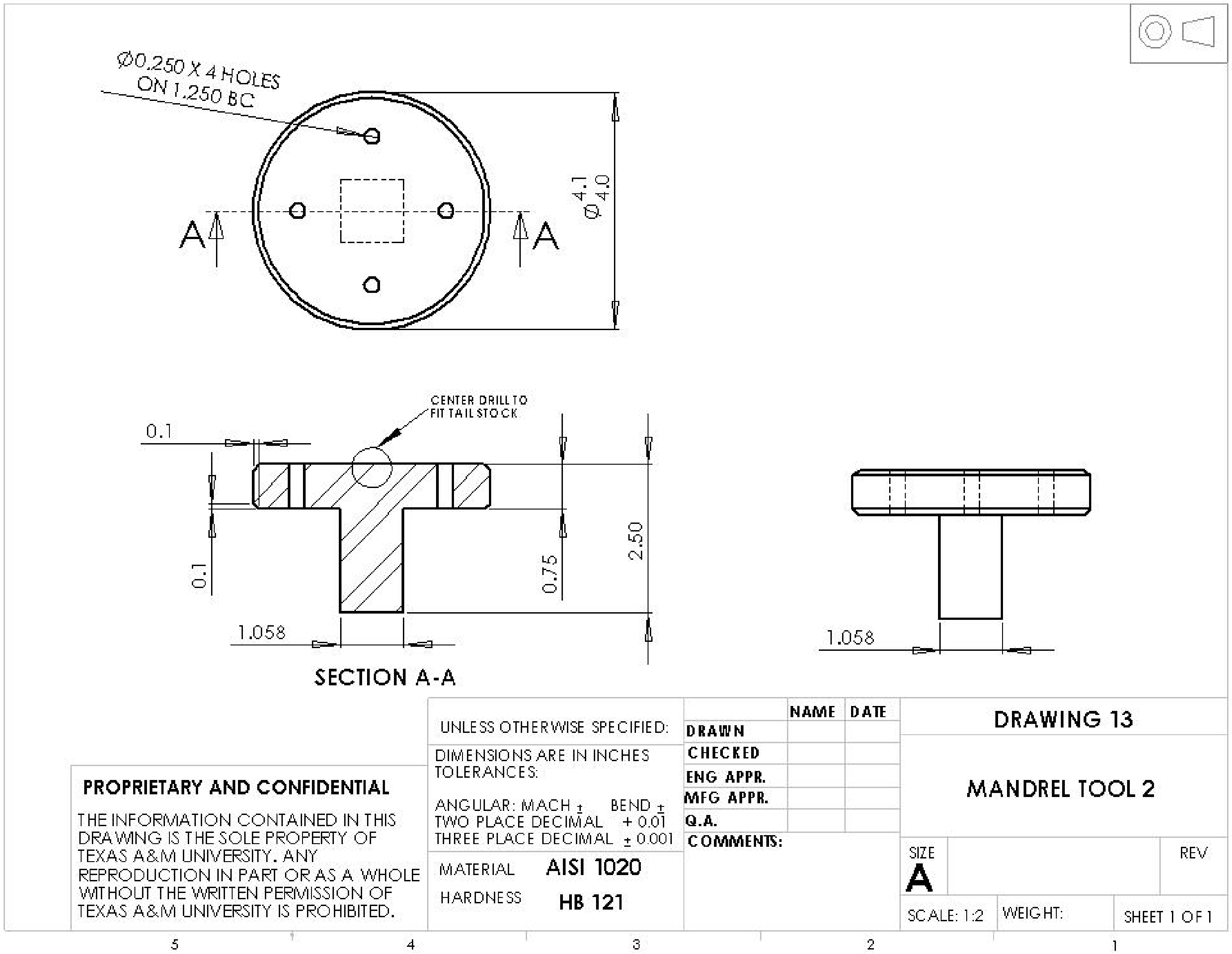


Fig. 31 **Mandrel tool for mounting and positioning individual wedges**

4.1.2 Material processing and heat treatment

The components of the area reduction extrusion tool should be annealed or normalized prior to machining. The heat treatment lowers the nominal values of the material's hardness, strength (yield and tensile) while enhancing the ductility. After machining, the wedges and die insert can be tempered to raise the material's strength and hardness once again. In order to machine the base plate, punch plate and flange locks, the bulk material (4140 steel) should be normalized by heating to a temperature range between 845 and 900 °C, followed by air cooling. At the end of the machining stage, the components should be hardened by heat treating to a temperature between 830 to 870 °C, oil quenching and then tempering at a temperatures of 480 °C. The container, which will be fabricated from 4340 steel, can best be machined by following the same normalizing operation described above and then tempering at a temperature of 650 °C to form a partly spheroidized structure. Following the machining process, the container should be strengthened by heating to a temperature between 800 to 845°C, oil quenching and then tempering at 425 °C. The wedges, die-insert and ram can be machined by annealing between 815 to 845 °C. Following machining, the components should be strengthened by austenitizing between 925 to 955 °C, oil quenching and then tempering at 425 °C. As for the mandrel tools (mandrel tool 1 and mandrel tool 2), they can be easily machined by choosing AISI 1020 in the cold drawn form.

A summary of the heat treatments required for each component prior to machining is presented within Table 13. Typically, the bulk material is acquired from the manufacturer in the heat treated form. In addition, the nominal room-temperature mechanical properties of the materials following final heat treatment are presented in Table 14.

Table 13 Summary of heat treatment of tool components prior to machining

Component	Material	Heat Treatment	Hardness (HB)
Base plate	4140 Steel	Normalize between 845 to 900 °C, then air cool	HB 187-229
Punch plate	4140 Steel	Normalize between 845 to 900 °C, then air cool	HB 187-229
Flange locks	4140 Steel	Normalize between 845 to 900 °C, then air cool	HB 187-229
Container	4340 Steel	Normalize between 845 to 900 °C, air cool, then temper at 650 °C	HB 187-241
Wedges	S7	Anneal between 815 to 845 °C	HB 187-223
Die-insert	S7	Anneal between 815 to 845 °C	HB 187-223
Ram	S7	Anneal between 815 to 845 °C	HB 187-223

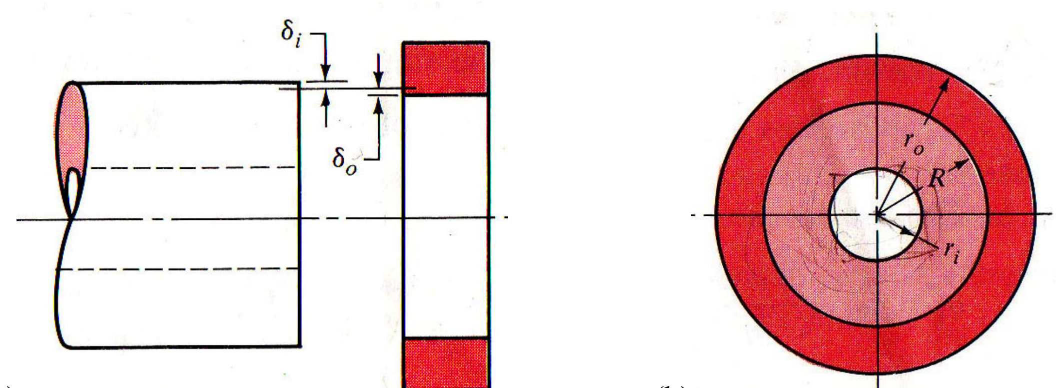
Note: HB refers to Brinell hardness and HRC is Rockwell hardness – C scale

Table 14 Nominal mechanical properties of materials heat treated after machining

Material	Tempering temperature (°C)	Yield strength (ksi)	Tensile strength (ksi)	Elongation 2 in. (%)	Hardness
AISI 4140	480	175	188	16	HB 388
AISI 4340	425	198	217	14	HB 440
S7	425	205	275	10	HRC 53

4.1.3 Required fits for assembled parts

Two cylindrical parts can be assembled by shrink-fitting a shaft into a hub, thereby creating a contact pressure between both surfaces. For the current tool, the process involves pushing the inner liner, which is typically at room temperature, into the preheated container. As such, it is possible to take advantage of compressive residual stresses which are imposed within the inner liner as a result of shrink-fitting the wedge/inner liner into the container. The residual stresses must be removed by the applied extrusion pressure before tensile stresses can form, thus making it possible for the container to sustain high service loads. The magnitude of the residual stresses induced by shrink-fitting is determined by the size of the interference fit between both parts. Figure 32 shows two cylindrical members that are assembled by shrink fitting.



(a) (b)

Fig. 32 Illustration of shrink fitting showing (a) unassembled parts, (b) final assembly [24]

As shown in figure 38, δ_i and δ_o represent the changes in the radii of the inner and outer members, while *R* is the transition radius that exists between both cylinders. A medium drive fit will be selected for the extrusion tool. The medium drive fit that will be selected is H7/S6 according to ANSI B4.1-1967 [24]. This standard uses tolerance position letters with capital letters for internal dimensional (holes) and lowercase letters for external dimensions (shafts) [24]. Terminologies that will be used and their associated definitions are:

1. Basic size (D): This is the size to which limits are assigned and is the same for both materials.
2. Deviation: Algebraic difference between a size and the corresponding basic size.
3. Upper deviation (δ_u): This is the difference between the maximum limit and the basic size.
4. Lower deviation (δ_l): This is the difference between the minimum limit and basic size.
5. Fundamental deviation (δ_F): This is either the upper or lower limit, depending on which is closer to the basic size.
6. International tolerance grade (ΔD): Specifies the tolerance zones, where the magnitude of the tolerance zone is the variation in part size and is the same for both internal and external dimensions [24].
7. Hole basis: This represents a system of fits corresponding to a basic hole size.
8. Shaft basis: This represents a system of fits corresponding to a basic shaft size.

The above definitions and how they apply to a cylindrical fit is shown in figure 33. Referring to figure 19, the basic size, 'D' of the hole within the container is $\phi 4.5$ inches. The tolerance specified for the container and wedges is determined by the medium fit selected. For the given hole size and the selected H7/S6 medium fit, the tolerance grade, 'ΔD' for the hole is 0.0014 inches according to ANSI B4.1-1967 [24]. As such, the maximum size, 'D_{max}' of the hole) is expressed in equation 30, while the minimum size, 'D_{min}' of the hole is the same as the basic size of the hole.

$$D_{\max} = D + \Delta D = 4.5014 \text{ in.} \tag{30}$$

As for the liners/wedges (shaft) shown in figure 20, the basic size is also $\phi 4.5$ inches. The tolerance grade of the shaft (Δd) is 0.0009 inches according to ANSI B4.1-1967 [24], while the fundamental deviation of the shaft is 0.0031 inches. Therefore the minimum size of the wedges assembled is ($d_{\min}$) is:

$$d_{\min} = d + \delta_F = 4.5031 \text{ in.} \quad (31)$$

while the maximum size of the wedge assembly is:

$$d_{\max} = d + \delta_F + \Delta d = 4.5040 \text{ in.} \quad (32)$$

The difference in the size of the container and the wedges creates the interference fit required to induce compressive residual stresses and to hold together the assembly of the wedges within the container. As for the other components of the tool assembly, clearance fits are provided to ensure easy assembly of the components and to restrict the displacements of some of the tool components while in service.

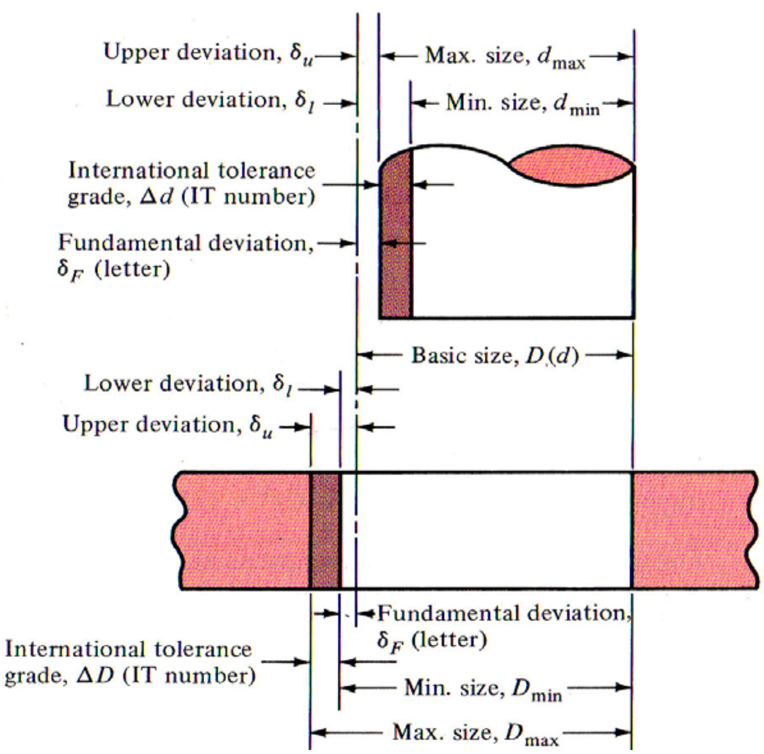


Fig. 33 Definitions applied to a cylindrical fit [24]

4.1.4 Evaluation of upper bound extrusion pressure

The composition and basic mechanical properties of materials that may be extruded by the area reduction tool are presented in Table 15. Based on these properties, the flow stress is assumed to be the material's ultimate tensile strength and used in the determination of the upper bound value of the extrusion pressure. Equation 19 as presented within the literature review is used to evaluate the upper bound value of the extrusion pressure for each material. The following assumptions are made when using equation 19:

1. Constant shear friction is assumed. This implies shear stress is proportional to the strength of the billet material. For the tool, a value of 1 is used for the friction factor 'm'.
2. Die is a rigid body.
3. Material follows Von Mises material behavior. This implies that the material is homogeneous, isotropic and non strain hardening.
4. Process must involve symmetric geometries and material flow is through a conical converging die.

Limitations to these assumptions can be caused by friction, which may exhibit a complex behavior that is different from the constant shear friction assumption. In addition the die, which is considered rigid, is expected to experience some limited form of elastic deformation. Furthermore, conversion of the billet's square cross section to an equivalent circular cross section for the purpose of evaluating the extrusion pressure may yield a value that deviates from the actual extrusion pressure that is observed.

The cone angle 'α' is a variable contained within the equation, which is evaluated independently by applying equation 20. Previously mentioned within the literature review, an optimal cone angle exists that minimizes the extrusion force. For the current problem, the initial billet cross sectional area of 1.00 in. by 1.00 in. translates to an effective radius of R-0.637 in. while the expected final cross section of 0.98 in. by 0.98 in. translates to an effective radius of 0.624 inches. When substituting the above values into equation 20, the optimum cone angle derived is approximately:

$$\alpha_{opt} \approx \sqrt{\frac{3}{2} m \ln(R_o / R_f)} = \sqrt{\frac{3}{2} * 1 * \ln\left(\frac{0.637}{0.624}\right)} = 0.176 \approx 10° \qquad (33)$$

f(α) is one of the factors present in the upper bound extrusion (equation 19) and its values are presented within [11], where *f(α)* = 1.00064. The upper bound extrusion pressure required for each material listed within Table 15 is displayed in Table 16.

Table 15 Composition and basic mechanical properties of fully worked materials to be processed by area reduction extrusion tool

Material (alloy)	Nominal Composition (wt %)	Yield Stress (ksi)	Ultimate tensile strength (ksi)	Poisson's ratio	Ductility (% Elongation)
Copper (C10100)	99.99 Cu	59	66	0.33	37
Ti	0.10 C, 0.25 O, 0.03 N, 0.3 Fe, balance titanium	94	103	0.34	16
Interstitial free steel (Ti added)	0.065 Ti, 0.050 Al, 0.002 O, 0.001 Ni, 0.008 S, 0.002 C, balance Fe	98	113	.3	34
Al6061-T6	0.4-0.8 Si, 0.7 Fe, 0.15-0.40 Cu, 0.15 Mn, 0.8-1.2 Mg, 0.04-0.35 Cr, 0.25 Zn, 0.15 Ti, 0.05 other, balance Al	40	45	0.3	17

Table 16 Upper bound extrusion pressure of materials

Material	Upper bound extrusion force (psi)
Ti	174,500
Steel (interstitial free)	192,200
Al6061-T6	76,500
Copper (C10100)	111,400

Previously discussed, the extrusion ratio is a factor that indicates the amount of reduction that a billet undergoes. The current area reduction extrusion tool uses replaceable die-inserts that make it possible to vary the reduction ratio. The value of the upper bound extrusion pressure at various flow stresses can be manipulated by varying the reduction ratio. For instance, a 6-in long copper billet (C10100) that is processed with this tool should begin to upset at 59 ksi and then start extruding at 66 ksi. The billet should undergo buckling around 57.8 ksi. Although buckling of the billet should occur prior to extrusion, the limited clearance that exists between the billet and liner enables the walls of the liner to prevent buckling by restricting lateral deformation of the billet.

Figure 34 shows a plot of the extrusion pressure vs. flow stress for various reduction ratios of the extrusion tool. In addition, the optimum cone-angle is plotted as a function of the reduction ratio in Figure 35. Based on the tool's extrusion ratio of 1.04, materials with flow stress values up to 100 ksi can be processed by the tool provided that the ram's safety factor is not considered.

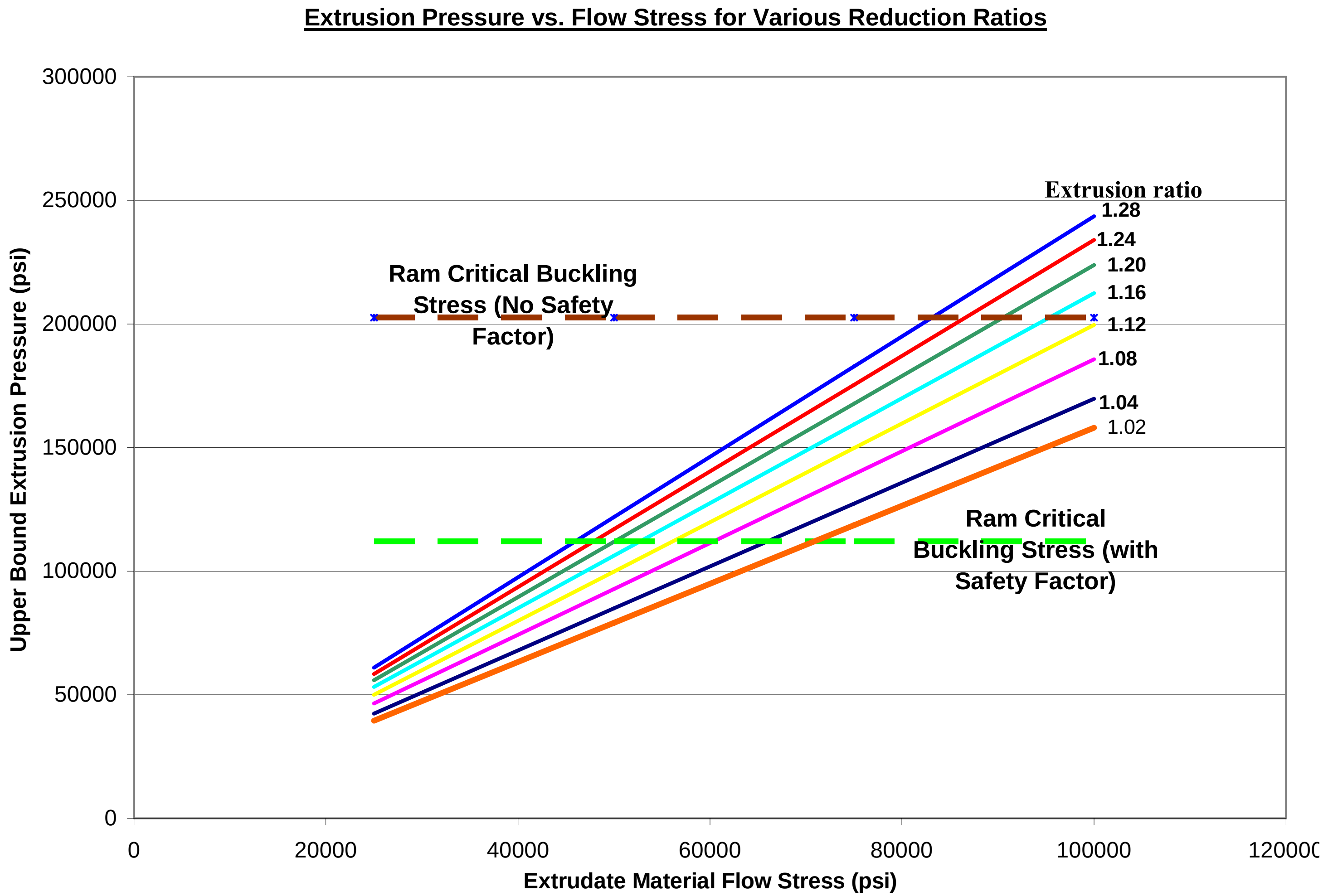


Fig. 34 **Variation of extrusion pressures for different extrusion ratios of the area reduction extrusion tool**

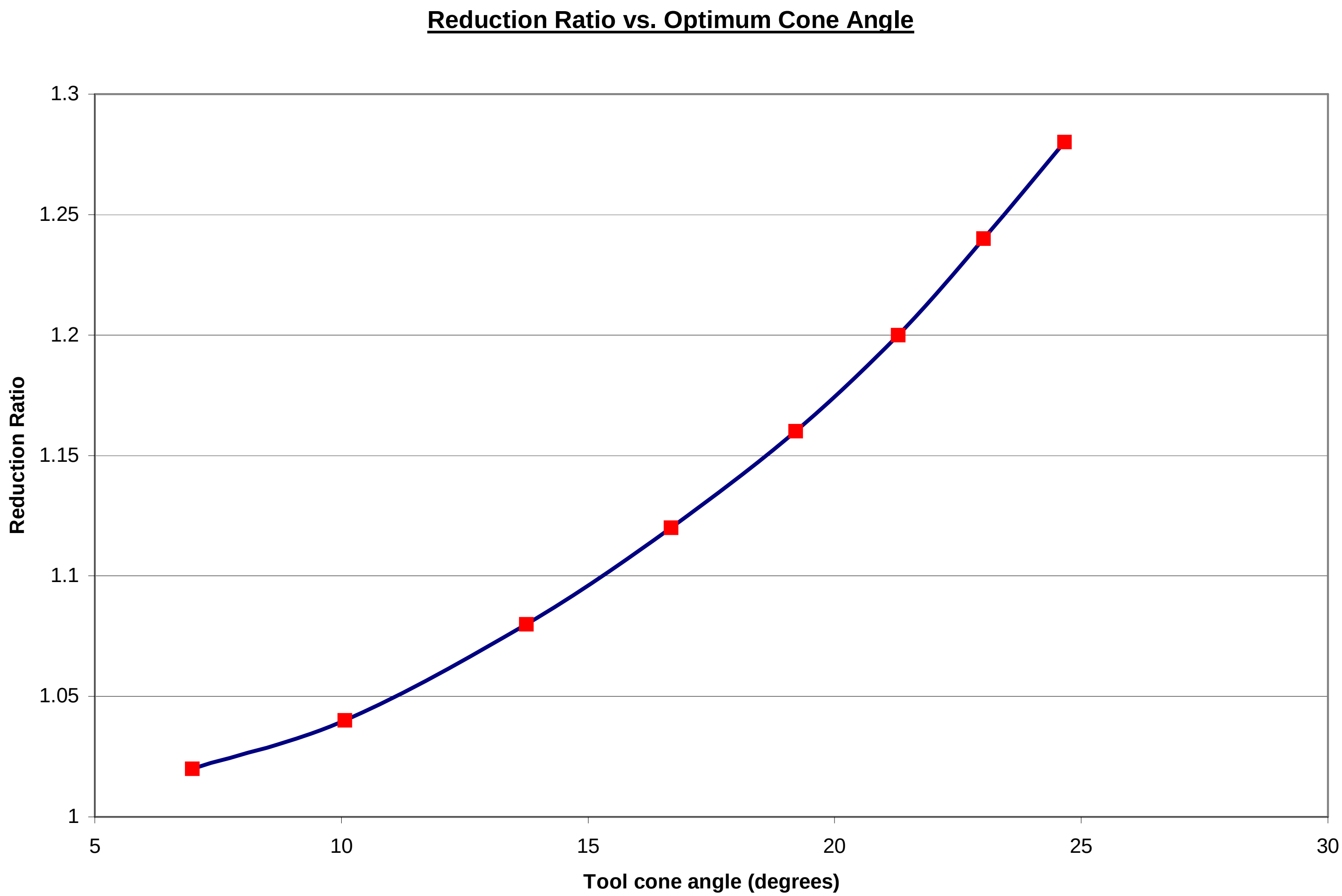


Fig. 35 **Optimum cone-angle as a function of tool reduction ratio**

4.1.5 Buckling of compression members

As mentioned previously, buckling is a phenomenon that may arise as a result of instability within the ram, thus leading to failure even before the compressive strength of the material is reached. For the current tool design, the probability of buckling within the ram is greatest at the start of the process where a greater portion of the ram is outside of the tool. This reduces as the extrusion progresses because the walls of the channel serve to restrict any lateral motion of the ram arising from compressive loads. The integrity of the design chosen for the ram is verified by evaluating the buckling limits of the ram under various end conditions and the results are presented as Euler buckling curves. In order to apply Euler's equations to the evaluation of buckling within the ram, the following assumptions are made:

1. The column is perfectly straight, with no initial crookedness. This implies that there is no bending moment in the member before buckling.
2. The load is axial, with no eccentricity.
3. The column is rounded at both ends.

In reality, eccentricity of load application may occur and the column may experience limited motion at the ends. As such, correction factors such as end condition factors are needed to address these situations.

Previously discussed within the literature review, punch buckling is evaluated by considering the material's elastic modulus, '*E*', slenderness ratio, '*L/r*', and end conditions, '*k*'. '*L*' is the effective length of the ram and '*r*' is the radius of gyration, which is equivalent to $\sqrt{I/A}$, where *I* is the moment of inertia and *A* is the cross sectional area of the ram. For the loading situation pertaining to the ram, the elastic modulus of the punch material is $30*10^6$ psi, while the effective length '*L*' is 11.03 inches. The end conditions that will be considered for modeling the load on the ram are: Rounded-rounded (Pinned-pinned), Rounded-fixed and Fixed-fixed. A value of 51.88 is established as the slenderness ratio at the transition point (C_c), which separates the Euler buckling curve into elastic and inelastic zones. Figure 36 displays the ram between the punch plate and die, which are quasi-fixed within the tool assembly. By considering the various end conditions, the effective length of the ram from figure 21 and the cross-sectional area of the bottom portion of the ram as the effective area, the slenderness ratio derived is less than 51.88 (C_c). This automatically leads to consideration of potential buckling as inelastic buckling according to the Euler curve of Figure 11. The Euler buckling curves describing the end conditions modeled for the given geometry of the ram are displayed as figures 37 through 39 with the critical unit load indicated on each curve. In addition, another geometrical possibility of the ram is considered as well by analyzing the ram as having a circular cross section and then plotting the Euler buckling curves with similar end conditions previously mentioned. The effective radius of the ram is determined to be R-0.615 in. by equating the circumference of the square cross section to the circumference of the circular cross section. The Euler buckling curves for the ram with circular cross section and the end conditions are presented as figures 40 through 42. Finally, the critical unit load determined for each cross section and the corresponding end conditions is summarized and presented in Table 17. Although, the fixed-fixed end condition best models the punch behavior once it is inserted into the area reduction extrusion tool, the rounded-fixed condition will also be assessed for subsequent calculations to account for any drift of the low portion of the ram within the area reduction extrusion tool.

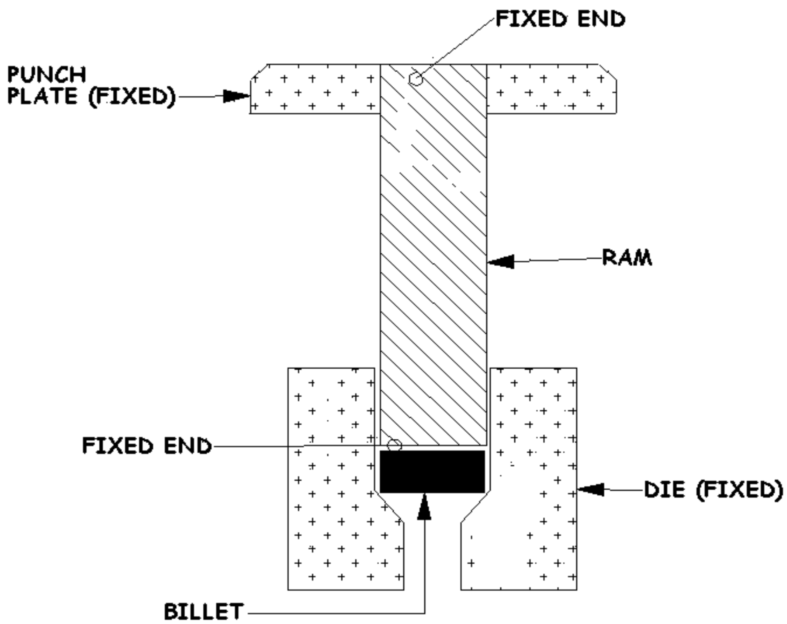


Fig. 36 Schematic of the ram revealing the fixed end conditions

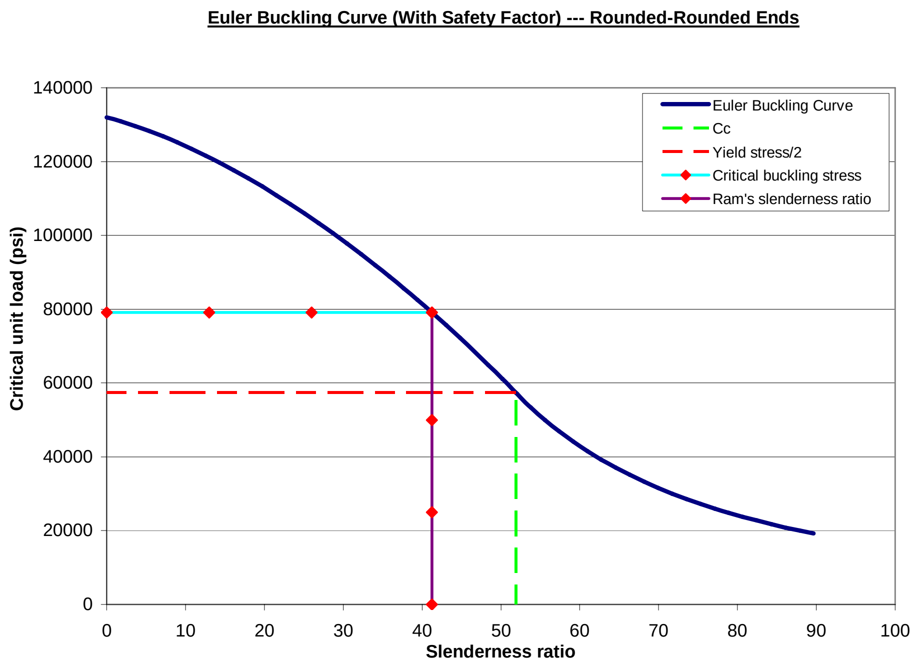


Fig. 37 Euler buckling curve for ram with rectangular cross section and rounded-rounded ends

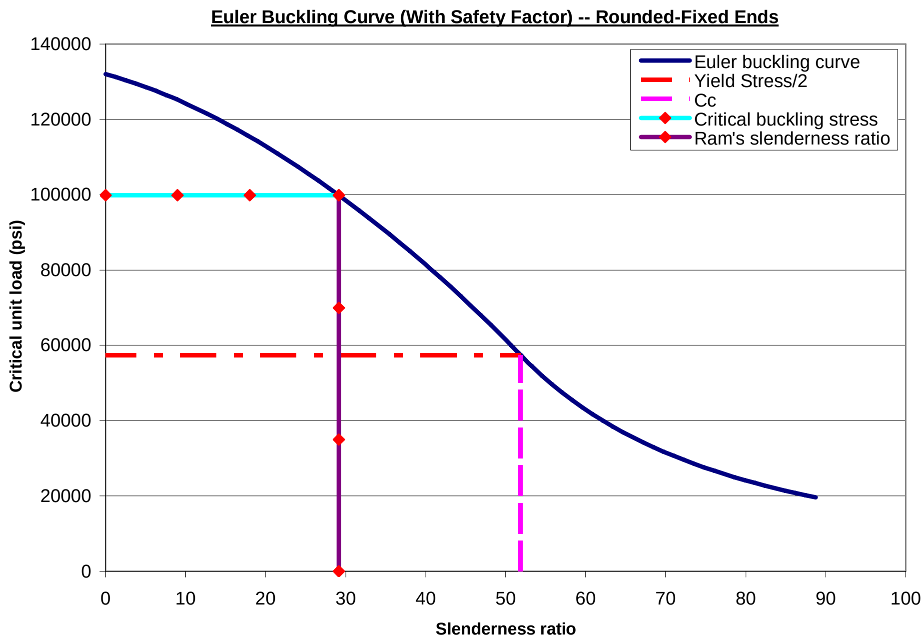


Fig. 38 Euler buckling curve for ram with rectangular cross-section and rounded-fixed ends

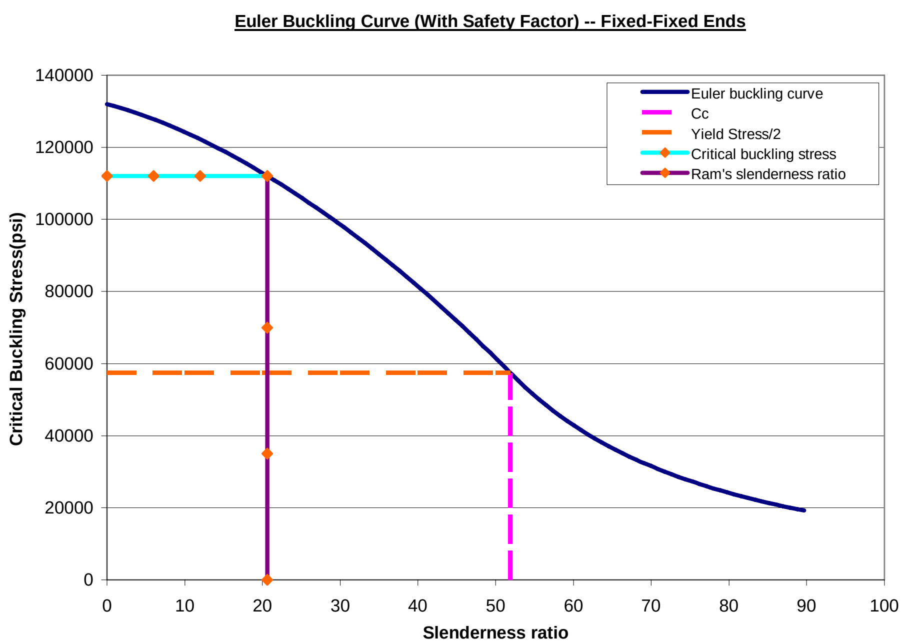


Fig. 39 Euler buckling curve for ram with rectangular cross-section and fixed-fixed ends

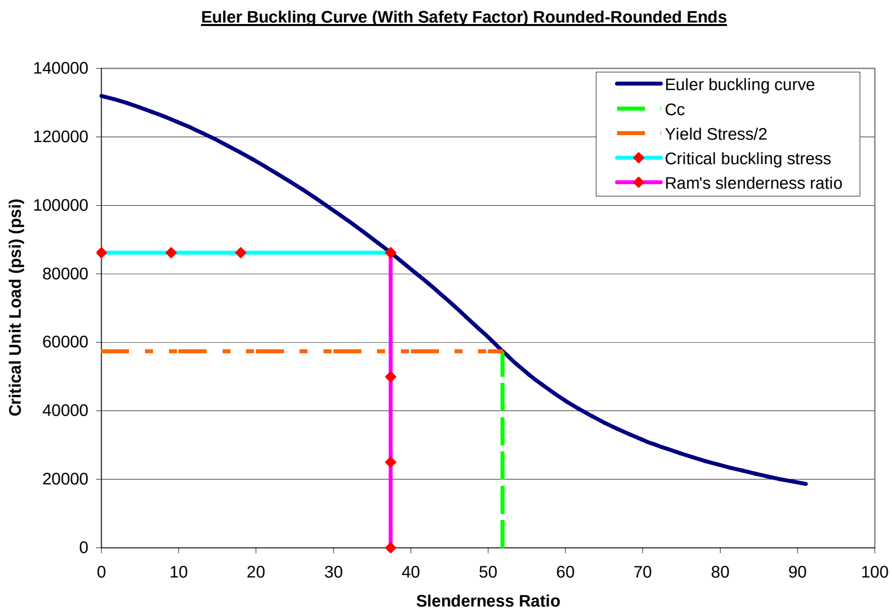


Fig. 40 Euler buckling curve for ram with circular cross-section and rounded-rounded ends

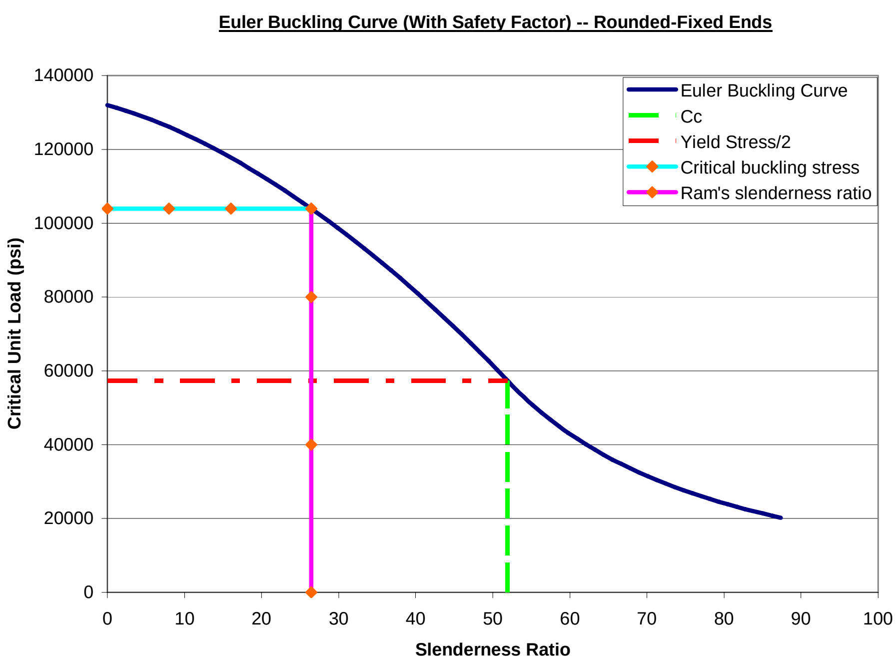


Fig. 41 Euler buckling curve for ram with circular cross-section and rounded-fixed ends

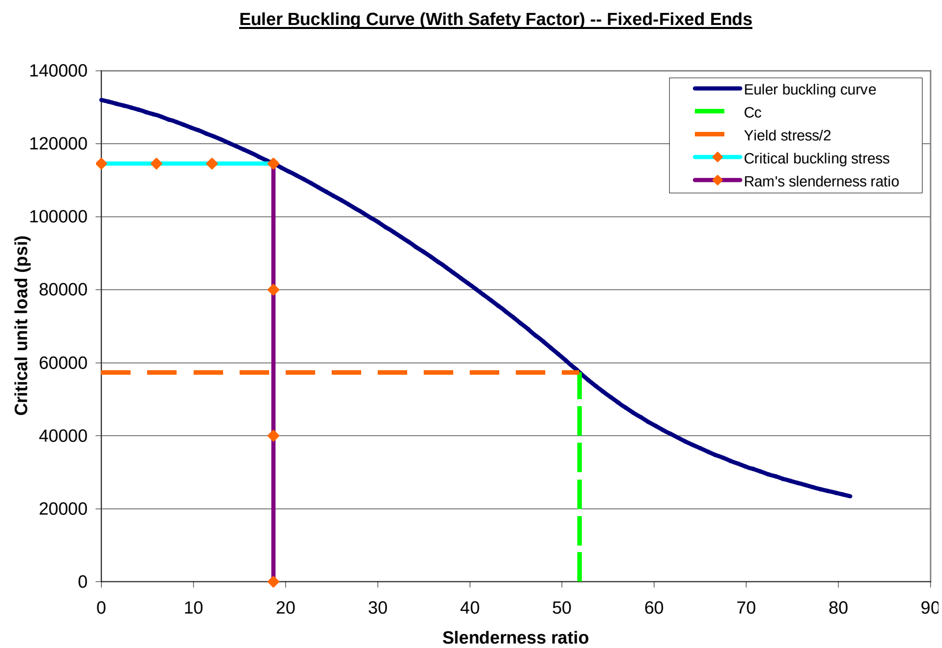


Fig. 42 Euler buckling curve for ram with circular cross-section and fixed-fixed ends

Table 17 Summary of critical unit loads for various end conditions and cross sections of the ram

Ram's cross section	**End conditions**	**Approximate Critical Unit Load With Safety Factor (psi)**	**Approximate Critical Unit Load Without Safety Factor (psi)**
Square	Rounded-Rounded	79 100	150 500
Square	Rounded-Fixed	99 900	185 300
Square	Fixed-Fixed	112 080	202 600
Circular	Rounded-Rounded	86 200	162 800
Circular	Rounded-Fixed	104 000	191 400
Circular	Fixed-Fixed	114 500	205 700

Based on the values presented in Table 16, a square ram of the given geometry in Figure 21 and fixed end conditions can sustain pressures up to 202 ksi without buckling. With the applicability of a safety factor to the design, the critical unit load is reduced to 112 ksi.

4.1.6 Lateral expansion of ram

In order to evaluate the maximum lateral expansion of the ram during operation of the area reduction extrusion tool, certain assumptions will be made. These include:

1. Uniaxial compressive state of loading on the ram.
2. An isotropic material.
3. An applied stress of 202,600 psi using a square cross section and fixed ends.

By applying the above assumptions, it is possible to use Poisson's ratio, 'v' to relate the axial strain of the ram to its lateral strain. Poisson's ratio is expressed in equation 34 below as:

$$v = -\frac{\varepsilon_x}{\varepsilon_z} = -\frac{\varepsilon_y}{\varepsilon_z} \tag{34}$$

where ε_z is the axial contraction (negative strain) in the direction of the applied stress and ε_x, ε_y are lateral elongations (positive strains) in response to the imposed compressive state of stress in the ram. By applying Hooke's law, which relates the stress to strain via a modulus of elasticity, it is possible to determine the axial strain ε_x. Based on the critical unit load of 202,600 psi (which excludes the safety factor) and the elastic modulus of the ram's material (S7), the value of the axial strain is:

$$\varepsilon_z = \frac{\sigma}{E} = \frac{202600}{30\times10^6} = 6.75\times10^{-3} = 0.00675\,\text{in./in.} \tag{35}$$

Since the ram is under compression, $\varepsilon_z = -6.75\times10^{-3}$. Therefore the lateral strains that are obtained are:

$$\varepsilon_x = \varepsilon_y = 0.3\times6.75\times10^{-3} = 2.03\times10^{-3} \tag{36}$$

The lateral strains obtained can be used to determine the amount of axial deformation that the punch is subjected to by applying the equation of engineering strain, which is:

$$\varepsilon_x = \varepsilon_y = \frac{l_f - l_o}{l_o} = \frac{\Delta l}{l_o} \tag{37}$$

where Δl is amount of lateral deformation, l_f is the width and l_o the original width before load is applied. From figure 21, the maximum width of the ram along each lateral direction is 1.044 inches. As such, the elongation along the lateral directions is:

$$\Delta l = l_o \varepsilon_x = 1.044 \times 2.03 \times 10^{-3} = 2.12 \times 10^{-3} \text{ in.} \tag{38}$$

Therefore the final length of each lateral surface is approximately:

$$l_f = \Delta l + l_0 \approx 1.046 \text{ in.} \tag{39}$$

Since the distance between each surface of the billet is 1.046 in., the final size of the punch is less than the size of the inlet channel of the tool. As such, there is no anticipated interference between the Ram and the Wedges during operation of the area reduction extrusion tool.

4.1.7 Stresses within the tool

The stresses developed within the container assembly are very important to the operational safety of the tool and also affect the geometry of the billet that emerges after area reduction. This is because the stresses arising from the deforming billet is transferred to the container assembly. At high pressures, cylindrical pressure vessels develop both radial and tangential stresses with values that are dependent upon the radius of the element under consideration [24]. Engineering calculations of the container wall stresses with the appropriate safety factors enables the determination of the working limits of the tool design and to establish if elastic deformations of the container assembly affect the geometry of the tool's channel. Although the tool will be used for cold extrusion processes, exposure to thermal stresses that are localized in nature will occur and these will be excluded from the engineering calculations of the container stresses for the purpose of simplification.

In order to determine the radial stress, 'σ_r' and tangential stress, 'σ_t' that form within the container assembly, the container is assumed to have constant longitudinal elongation around its circumference. As such, the service stresses formed within the container assembly can be determined by applying the equations of a thick walled pressure vessel. The applicable equations are:

- *Tangential Stress (thick wall pressure vessel):* $\sigma_t = \frac{r_i^2 p_i}{r_o^2 - r_i^2}\left(1 + \frac{r_o^2}{r^2}\right)$ (40)

where the inside radius of the cylinder is designated by r_i, the outside radius of the cylinder r_o, the radial distance along the cylinder wall by r and the internal pressure by p_i.

- *Radial Stress (thick wall pressure vessel):* $\sigma_r = \frac{r_i^2 p_i}{r_o^2 - r_i^2}\left(1 - \frac{r_o^2}{r^2}\right)$ (41)

It is important to realize that equations 40 and 41 are applicable only at sections taken at a significant distance away from the ends of the container and at any areas of high stress concentration. The present design of the tool compensates for the effects of stress concentration within the container assembly by an increased wall thickness of the container around the region where the die assembly is installed. In order to apply the above equations to the tool, certain simplifying assumptions are made to determine the stresses within the walls of container assembly. These assumptions are:

1. Exclusion of the taper angle within the container assembly in order to consider the wedges and container as purely cylindrical entities.
2. Longitudinal elongation is constant around the circumference of the cylinder. This implies that a right section of the cylinder remains plane after stressing.
3. The square walls along the die land will be converted to an inside radius by employing a parameter termed the effective radius, 'r_i', which is derived by equating the perimeter of the square cross section to the circumference of a circle .

Furthermore the maximum extrusion pressure sustained by the container is limited by the ram's critical unit load of 202,600 psi as specified within Table 17. From Table 16, interstitial free steel has an upper bound extrusion pressure (192,200 psi) slightly less than the ram's critical unit load. At this maximum extrusion pressure, the material has a flow stress of 113 ksi as specified within Table 15. By substituting the flow stress of 113 ksi as 'p_i' within equations 40 and 41, it is possible to determine the values of the tangential and radial stresses sustained by the walls of the container assembly. For the die assembly, the square cross sectional area of 0.98 in. by 0.98in. yields an approximate effective radius of 0.624 in. In addition, the basic size of 2.25 in. (excluding the effect of the taper) is used as the outer radius of the wedge/liner assembly. As for the container, the inside radius used is 2.25 in., while the outside radius selected is 4.0 in. The outside radius selected for the container neglects the effects of the additional wall thickness provided at the bottom in order to provide a baseline value of the wall stresses.

Prior to evaluating the service stresses that form in the wall of the container assembly, it is important to determine the contact pressure 'p'. The contact pressure is formed at the transition radius 'R' that exists between the liner/wedge and the container as a result of shrink-fitting the liner into the container. The magnitude of the stresses induced by shrink-fitting can be controlled by the size of the interference fit between the liners and the container [21]. Certain simplifying assumptions are made to quantitatively assess the residual stresses induced by the shrink-fitting process. These assumptions are [19]:

1. Symmetrical stressing of the container and inner liner around its axis.
2. Temperature distribution is axisymmetric over the full length of the container assembly.
    a. Local thermal stresses, which cannot be calculated, are neglected.
    b. Longitudinal thermal stresses arising from shrink-fitting are excluded.
3. Materials used for the container and inner liner have the same modulus of elasticity and the state of stress is purely elastic.

In order to determine the contact pressure, it is necessary to determine the radial interference, 'δ' by applying the following equation [24]:

$$\delta = |\delta_i| - |\delta_o| \tag{42}$$

where δ_i and δ_o symbolize the changes in the inner and outer members, respective [24]. The contact pressure 'p' can be solved once the radial interference δ is known by applying the following equation [24]:

$$\delta = \frac{pR}{E_o}\left(\frac{r_o^2 + R^2}{r_o^2 - R^2} + \nu_o\right) + \frac{pR}{E_i}\left(\frac{R^2 + r_i^2}{R^2 - r_i^2} - \nu_i\right) \tag{43}$$

Since the materials selected for fabricating the liner and container are similar, values of the elastic moduli and poisson's ratios are similar. As a result, equation 39 can be simplified to:

$$p = \frac{E\delta}{R}\left(\frac{(r_o^2 - R^2)(R^2 - r_i^2)}{2R^2(r_o^2 - r_i^2)}\right) \tag{44}$$

A value of 0.003 inches is determined to be the radial interference based on the medium fit H7/S6 chosen for the container assembly. The effective operating stresses (resultant stress) that act on the container assembly can now be obtained by superimposing the service stresses arising from the extrusion pressure and the residual stresses created by the shrink-fitting process. The resultant stress 'σ_R' is determined by applying the strain energy hypothesis according to the following equation [19]:

$$\sigma_R = \sqrt{\sigma_t^2 + \sigma_r^2 - \sigma_t.\sigma_r} \tag{45}$$

The resultant stress multiplied by a safety factor 'k', with a value of 1.3 must not exceed the high temperature proof stress '$R_{p0.2}$' of the materials used for the container assembly. This is because the shrink-fit stresses formed within the container assembly will not be retained and the container will suffer permanent plastic deformation [24].

$$\sigma_R.k < R_{p0.2} \tag{46}$$

A summary of the anticipated service stresses, residual stresses, total stresses and resultant stresses, which container is expected to sustain is presented in Table 18.

Table 18 Stresses formed within the wall of the container and wedges

Section of tool wall	Type of stress	Service stress (psi)	Residual stress (psi)	Operating stress (psi)	Resultant stress (psi)
	Radial stress	-31,980	-6,470	-38,350	
Inner surface of container					99,010
	Tangential stress	61,570	12,450	74,020	
	Radial stress	0	0	0	
External surface of container					35,580
	Tangential stress	29,600	5,990	35,590	
Inner surface of liner		113,000	0	113,000	113,000
External surface of liner		31,980	-6,470	25,510	25,510

The inner wall of the liner/wedge has to withstand the highest operating stresses, with a value of 113 ksi. By applying the safety factor '*k*' of 1.3 to the resultant stress at the inner wall of the liner, an approximate value of 147 ksi is obtained. This value is less than 175 ksi, which is the high temperature proof stress of AISI 4140 at 480° C as specified in Table 14.

4.1.8 Bolt sizing and the effects of tool land length and width on emerging billet

The land length, which is a feature on the Die-insert, is designed to straighten the billet upon undergoing area reduction. Each billet that is processed by the tool should emerge with a square cross section of 0.98 in. by 0.98 in upon undergoing area reduction.

Although the billet is subjected to plastic deformation, some fraction of the total deformation is recovered as elastic strain upon emerging from the land [26]. This elastic strain causes the size of the billet to increase along the lateral cross section ultimately affecting the final dimensions of the exiting billet. In addition, this strain energy could possibly alter the parallelism of the emerging billet. For each material that is a candidate for area reduction, the elastic strain that is recovered is determined and presented in Table 19. In addition, the final size of the cross section that emerges is revealed as well.

Table 19 Effects of elastic strain recovery on billet emerging from extrusion tool with exit dimensions of 0.98 in. by 0.98 in.

Material	Lateral Strain ε_x, ε_y (in/in)	Final cross section (in^2)
Copper (C10100)	$1.31 * 10^{-3}$	0.981 * 0.981
Ti	$2.35 * 10^{-3}$	0.982 * 0.982
Steel (Interstitial free)	$1.17 * 10^{-3}$	0.981 * 0.981
Al6061-T6	$1.35 * 10^{-3}$	0.981 * 0.981

Operation of the extrusion tool could lead to the formation of flash, which may travel between the Ram and the wall of the inlet channel. The flash may cause the Ram to get stuck within the tool thus requiring the need for a force larger than what is typically needed to retract the Ram from the tool. As a result, machine screws are required to restrain any vertical motion of the tool assembly resulting from the retraction of the Ram from the tool. The machine screw specifications are rated based on anticipated service loads that may occur during retrieval of the Ram from the tool.

In order to rate the machine screws, certain assumptions are made. These include:

1. A maximum axial pressure on the Ram that is equal to the tensile strength of interstitial free steel
2. Equal distribution of the force on the machine screws
3. Flash formation on each of the ram's four surfaces with an approximately area of 1-in^2
4. A torque that can be determined from the following empirical equation:

$$T_i \cong 0.21 F_i d \tag{47}$$

where T_i is the tightening torque needed to obtain a desired preload force F_i and d is the nominal diameter of the screw. By selecting a machine screw with an SAE grade number '8', the minimum proof strength is 120 ksi according to SAE specifications [25]. The proof strength is a value lower than the material's yield strength and it is the point at which the machine screws begin to take a permanent set. For a maximum axial pressure of 113 ksi (ultimate tensile strength of interstitial free steel) and surface friction coefficient of 0.1, the total axial load determined is 45,200 lbs. Equal distribution of the load across each bolt results in a maximum load of 11,300 lbs. The proof strength is used to determine the preload on the machine screw according to the following equation:

$$F_i = 0.75 S_p A_t \tag{48}$$

where S_p is the proof strength and A_t the tensile stress are (0.226 in^2) of the machine screws [25]. Based on the given values and equation 48, the preload is approximately 20,340 lbs. By applying equation (47), an approximate tightening torque of 2,670 lbs-in is determined. Major failures that may occur within the tool and the associated stress values are given in Table 20.

Table 20 Failure possibilities and associated failure loads of tool components

Possible failure modes	Approximate Failure strength (ksi)
Container rupture from internal pressure	217
Punch buckling	203
Tensile failure of tie-down bolts used with flange lock	120
Shear failure of throat on die-insert	101

4.2 *Manufacturing Methods for the Tool*

The manufacturing methods selected to construct the tool are just as important as the engineering analysis performed to design the tool. This is because the quality of finish, cost and deviation of the dimensions of individual tool component from specified values is highly dependent on the manufacturing process selected. As a result, manufacturing processes that will be used for the various tool components are described below.

The base plate, punch plate, die inserts and flange locks can each be shaped on a lathe followed by the creation of the holes on each component with a drill bit that is mounted on a mill. In addition, the ram and punch each can be fabricated on a lathe as well. As for the wedges, they can be fabricated by following the detailed steps below:

1. Get a round stock with the following approximate dimensions:
   Diameter: 5 inches, Length: 14 inches.
2. With the raw stock mounted on a mill, use a slitting saw to divide the stock into 4 quarters (wedges) (see figure 43).
3. Take off 0.530 inches from the inner edge of each wedge (see figure 43).
4. Assemble the wedges together onto both mandrel tools.

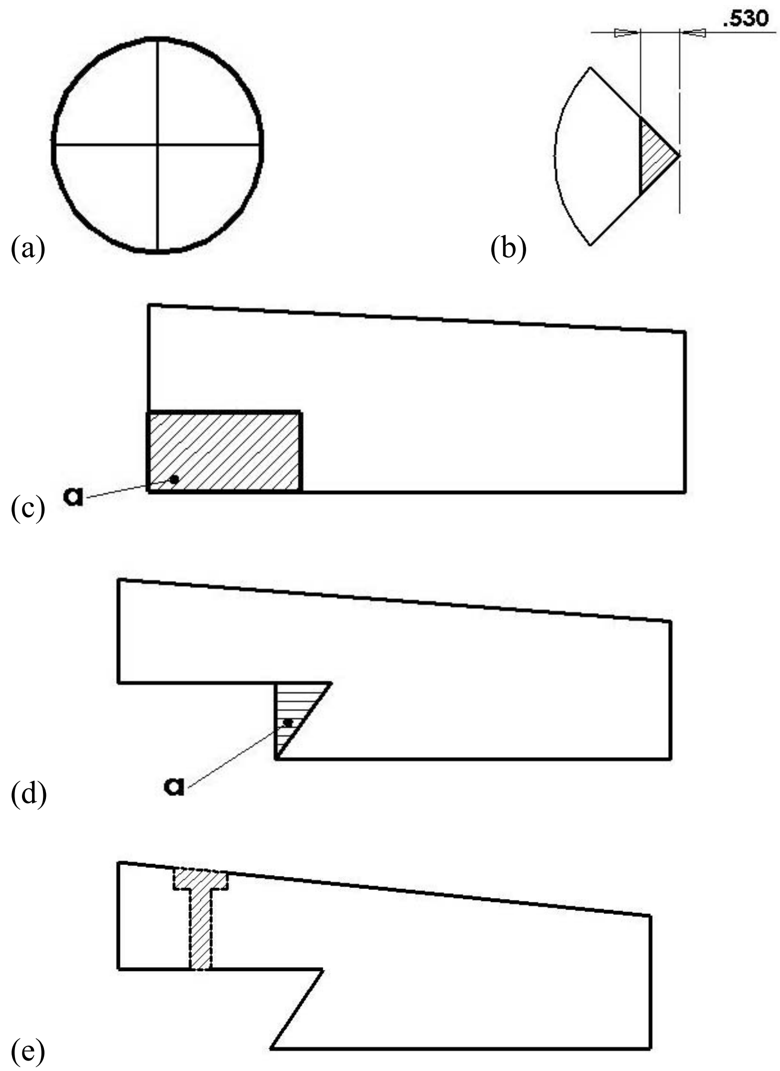


Fig. 43 Machining steps to fabricate wedge. (a) step 2, (b) step 3, (c) step 10, (d) step 11, (e) step 12

5. Drill a ¼ inch diameter hole through the upper mandrel into the wedge. Depth of the hole should be about ½ inch into the wedge.
6. Position alignment pins into the drilled holes.
7. Insert bottom mandrel into the chuck on the lathe, while upper mandrel is supported by tail-stock.

8. Turn down the wedge to the desired diameter with the proper taper setting on the hole.
9. Cut the wedge to the desired length with a mill.
10. Place the wedge on a mill and take-off a rectangular groove (cross hatch) at the bottom of the wedge (see figure 43).
11. Cut the additional taper (cross hatch a) into the wedge using a mill (see figure 43).
12. Create the holes for the cap screw using the mill (see figure 43).
13. Create chamfer on the ends of the wedge.

4.3 *Standard Operating Procedure for the Tool*

The method of operation of the assembled area reduction extrusion tool is described below.

1. With the aid of a hydraulic press, the punch is withdrawn from the inlet channel of the extrusion tool to a height clear of the top surface.
2. The punch is then translated horizontally to reveal the inlet channel of the tool. A T-section is responsible for supporting the punch plate as well as providing the means to move the punch laterally away from the inlet channel of the extrusion tool
3. Next the work piece is inserted into the area reduction extrusion tool.
4. The punch is placed above the inlet channel of the extrusion tool.
5. The hydraulic press is activated to supply the power that will create downward motion of the tool. The velocity of the punch will be dependent on the strain rate that is required to minimize the formation of defects within the work piece.
6. The compressive force that is applied by the ram on the work piece causes the work piece to deform through the die and exit the extrusion tool through the opening within the base plate.

4.4 *Summary of Results*

The results of the engineering analysis related to the tool design are summarized below.

1. For the given tool with an exit cross section of 0.98 in. by 0.98 in. and extrusion ratio of 1.04, the upper bound extrusion pressure required was lowest for Al6061-T6 (76.5 ksi) and highest for the interstitial free steel (192 ksi). The extrusion pressure is limited by the critical limit load (psi) of the Ram. For the ram's square geometry, the pressure drops to 112 ksi with the application of a safety factor.
2. The buckling limit of the ram depends on geometry. For a round billet and ram with circular cross-section, the critical unit load (psi) is much higher compared to one with an equivalent square cross section. In addition, the end condition of the ram affects the value of the critical unit load regardless of the cross section. For the cross sections considered, the critical unit load is highest with both ends of the ram fixed. However, modeling the ram with rounded ends results in critical unit loads much lower than other the other end conditions.
3. Due to Poisson's effect, elastic deformation of the Ram occurs in the lateral direction whenever the billet is being extruded. The critical unit load of 202 ksi causes lateral deformation by 0.002 in. along each lateral direction. As a result of the 0.007 in. gap between the ram and chamber walls, there is no anticipated interference between the ram and the wedges during processing.
4. Within the wedges, any stress formation arises from the internal load caused by flow of the billet. The stresses in the container are created by a combination of loads internally, which arise from extruding the billet and the effects of press-fitting the wedges into the container. The maximum resultant stress in the wedges and container occur on the inner surface. For the container the maximum resultant stress is 99 ksi, while the wedge has a maximum resultant stress of 113 ksi. A safety factor of 1.5 keeps the stress

on each component under the yield stress and within safe operating limits of the material.

5. Due to the selection of a medium drive H7/S6 fit, a lower and upper bound of 0.001 and 0.004 are determined as the interference size between the wedges and the container. Heat treatment of each material should be done prior to component fabrication. Components fabricated from 4140 steel should be normalized and air cooled before machining. As for the components fabricated from S7 tool steel, annealing is required prior to machining. The inner surface of each wedge and the die should be machined to a fine surface finish.

5. CONCLUSIONS

The objective of this study: to design an area reduction extrusion tool for reshaping ECAE processed square cross section bars has been reached. The imposition of external constraints such as the channel size, geometry of the billet and the ability to process a range of materials was achieved in the tool design. This was possible by addressing the functionality of the different tool components and then generating configurations that were evaluated against different criteria such as the extrusion pressure, materials selection and manufacturability.

Although a simple tool design was advanced, an important feature involved using four wedges that would be press-fit into a container to form the required square geometry of the tool's channel. This made it possible to address the key issue of stress concentration that typically is at the fore front of failure within tools of such channel geometry. In addition replaceable die inserts, which serve multifunctional purposes, were included within the tool design. As a result, the tool is able to process area reductions of different sizes (varying extrusion ratio) and also reduce downtime and cost associated with replacing worn/damaged dies is reduced.

The theoretical value of the upper bound extrusion pressure needed to extrude materials with different flow stresses was determined. Although, the yield stress of the material used for the ram typically limits the extrusion pressure, buckling behavior is the determining factor driving the design of the tool by imposing the maximum pressure that can be processed by the tool. Although, the ram may experience slight localized rotation at the lower end, fixed end conditions best represent the loading condition while in service. The critical buckling stress is much higher for a ram with fixed ends compared to one with rounded ends or a rounded and fixed end. In addition the slenderness ratio, which is a culmination of the ram's geometry, end conditions and dimensions, reveals that potential buckling of the ram will be of an inelastic nature when analyzed with an Euler buckling curve.

An adequate amount of tolerance (0.007 in. min.) between the ram and wedges prevents any interference that may occur due to lateral elastic deformation of the tool during extrusion. An increase in the extrusion ratio of the tool raises the upper bound extrusion pressure. If the safety factor of the container assembly and ram are excluded, the extrusion ratio of the tool can vary from 0.00 to 1.28. This places an upper limit of 82,000 psi on the flow stress of any material to be processed by the current tool. If safety factors of the above components are considered, the flow stress is reduced by a factor of two.

Heat treatment of the tool components by normalizing (AISI 4140) and annealing (AISI 4340 and S7 tool steel) improves their machinability considerably. The medium interference fit, H7/S6, selected for pressing the wedges into the container provides residual compressive stresses that reduce the wall stresses during extrusion.

The results of the study show that a simple design can be used to achieve the goal stated within the need statement. Although the tool design provides a baseline solution to the need statement, there are limitations to the design spawned by the operating loads that can be effectively supported within applicable safety limits.

6. RECOMMENDATIONS FOR FUTURE WORK

There remain some unresolved issues pertaining to the current tool design. First off, a way to quantify the effects of the land length on the required extrusion pressure and geometry of the reshaped billet is yet to be developed. This is because the land length affects the extrusion pressure through the friction that is formed between the billet and the land during extrusion. Connecting the tool to a power supply is another issue that needs resolution. The type and size of the hydraulic device to be incorporated coupled with the working environment are important parameters to be considered as well. In addition, a device for removing the wedges from the container should be designed and fabricated as well. The quality of the billet upon emerging from the tool is another factor that needs consideration. The billet should be checked for surface and internal defects that may arise as a result of the tool design in order to incorporate any corrective measures.

Other recommendations for a next generation tool are outlined below. These include:

1. Upon fabricating and commissioning this tool, extrusion data (load) that is recorded during the tool operation should be correlated with theoretical value determined by the upper bound method. If significant disparity is observed, other analytical methods such as the slip-line and slab methods should be tested to determine the most suitable method of estimating the extrusion pressure given the same original parameters.
2. Detailed finite element studies of the current tool would be helpful in identification of tool stresses throughout the assembly and at critical locations. Armed with this knowledge, the design of a second generational tool should incorporate this vital information with the aim of optimizing tool design via reduction of the limiting service loads.
3. The formation and behavior of flash within the tool should be investigated. Excessive flash typically raises the needed extrusion pressure and possibly

the retrieval load for the ram after extrusion. The effects of different lubricants on the surface of the tool and their relationship towards the accumulation of flash and the ram's retrieval load should be studied.

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