Extrusion Productivity: Billet Geometry/Container/Dummy Block

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ABSTRACT – This paper studies the impact of process parameters on press productivity. In particular, 3D simulations have been performed to determine the effect of billet geometry (that is primarily billet length and diameter) on press load, extrusion temperature and mode of deformation in the billet. Such simulations are shown to be invaluable to the extruder to allow optimization of the container dimensions, tooling, and die design, which leads to maximizing productivity.

INTRODUCTION

When extruders decide to install a new press, they naturally consider the product mix, profile size, and weight (lbs/ft.). Depending on the run-out table, this determines the ideal billet weight. They choose a press tonnage usually based on the billet diameter and the requirement of a certain dummy block pressure. Maximum extrusion speed is achieved when pushing the coldest possible billet; in other words, when the press load is at a maximum at breakthrough. With that requirement, all that is needed for high productivity are pumps that can deliver a high ram speed.

One additional question arises, which is the subject of this paper: what is the best billet geometry? This question is concerned with a geometry (combination of diameter and length) that minimizes the press force, and therefore allows billet temperature to be minimized and extrusion speed to be maximized. Billet diameter may vary from 3 inches to 33 inches, while 7-inch to 9-inch billet diameters are the most common and standard billet length and may vary from 26 inches to 72 inches.[1]

To take advantage of the press capacity and runout table size, it is recommended to maximize the billet length, [2] but it is certainly important that one should not blindly increase billet length or billet diameter and expect improved productivity, especially if this creates problems with other parts of the process, such as: dummy block functioning, extrusion dimensions, butt shearing, material flow, [3] etc. Increasing billet weight will likely increase contact utilization, [4] but it might not increase productivity; it might do the opposite. This is the subject that is addressed in this paper.

WHAT IS THE BEST BILLET GEOMETRY?

Many extruders are tending to move to longer billets. They report higher contact utilization with longer billets, and perhaps assume that this means higher productivity. With the more common use of front-loading presses, it is now simple to increase the maximum billet length. Clearly, extruders producing coiled product might prefer longer billet lengths at lower speed. For regular extruders, it is not immediately obvious which choice is the best option that allows the highest extrusion productivity.

To produce the same length of profile, the extruded volume/weight of the billet must be kept constant. For example, if the diameter of the billet is reduced (via a smaller container), then the billet length must be increased. On the other hand, to preserve productivity while reducing the billet diameter, the ram speed must be increased to compensate for the reduced extrusion ratio.

In this paper, a series of simulations are performed to analyze the effect of billet length and diameter on the extrusion load and exit temperature, while keeping the extrusion speed (productivity) constant. Then, the predictions for pressure and loads were used to study the effect of billet geometry on the dummy block, container, and die.

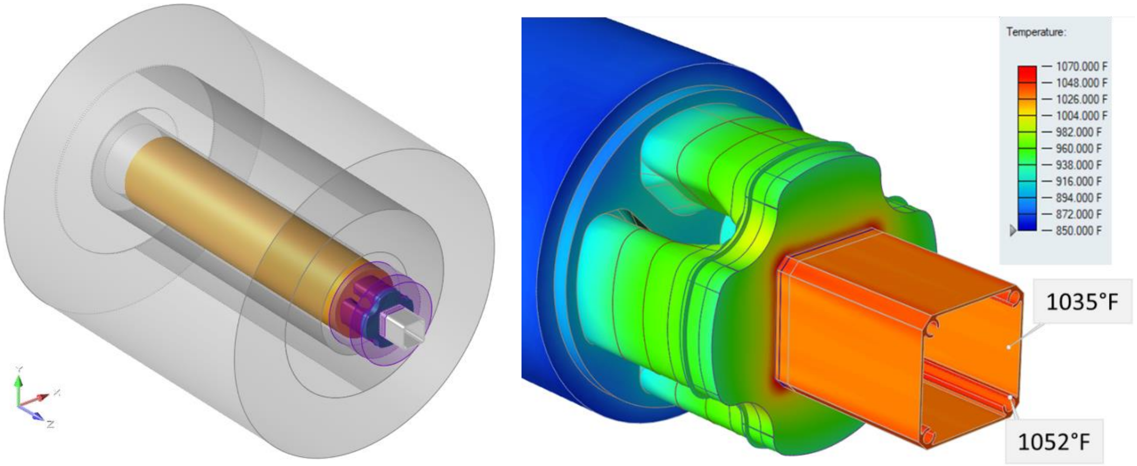
Parametric Study with Simulation

Altair's HyperExtrude® finite element (FE)-based code is used for thermomechanical 3D simulation of the extrusion process. Figure 1 shows the model geometry and temperature distribution inside the die, and in the profile at die exit during extrusion with an 8-inch billet. The extruding material is a standard AA6063 alloy. A Sine Hyperbolic constitutive equation was used to define the deforming AA6063 material's hot flow stress:

$$A\,[\sinh(\alpha\,\sigma)]^{n} = \dot{\varepsilon}\,\exp\left(\frac{Q}{RT}\right)$$

Where σ, $\dot{\varepsilon}$, and T, are flow stress (MPa), strain rate (1/s), and temperature (°K), A, α, n, and Q are material constants and their values are 5.91052e + 09 s^{-1}, 0.04MPa^{-1}, 5.385, and 141.55kJol/mole.[5] R is the universal gas constant (8.314 J/moleK).

The billet and die preheat temperature is 850°F and that of the container is set to 800°F. The simulations are performed at steady-state conditions to represent the conditions after several billets are extruded, when the process reaches a semi-steady thermal balance.



(a) (b)

Figure 1. a) 3D Extrusion model geometry; and b) Temperature distribution in the profile at die exit (8-inch billet, at 30in/min ram speed and 140ft/min profile speed).

Billet diameter and billet length are taken as variables with two levels. A factorial design with a center point (five runs) was applied for simulation experiments (Table 1). Billet diameters of 7-inch, 8-inch and 9-inch and billet lengths of 32-inch, 48-inch and 64-inch are covered. The ram speed is adjusted for each case, so that the exit profile speed is identical at 140ft/min (equivalent to ram speed of 30in/min with an 8-inch billet).

Table 1 summarizes the loads and temperature results for all cases during extrusion, including extrusion load (load on dummy block), portions of load on container and die set, average pressure at the dummy block face, and exit temperature. There are two values reported for exit temperature: maximum and average. The maximum temperature at the exit stands for instantaneous maximum temperature across the section of profile at the die exit. In Figure 1, there are two temperature callouts showing the instantaneous temperature of two points on the profile a few inches after the die exit, at the tip of an internal edge (1052°F) and at the middle of a wall (1035°F). The average exit temperature for the same case is 1042°F that falls between both. But which one is being measured by pyrometer during extrusion? It is most probably the wall temperature (1035°F), which is usually the lowest among the mentioned values.

Figure 32 and Figure 23 exhibit how moving from long and thin billets to thick and short billets would decrease both exit temperature and pressure on the dummy block (with same profile/puller speed). These are in favor of using thicker and shorter billets. Table 1 extrusion load would increase significantly. But the good news is that due to lower exit temperature with higher billet diameter, a higher preheat temperature can be used if a drop in load is of interest (where press load capacity is reached) or increase the ram speed to increase productivity if the press capacity allows. Model predictions show that using larger billet diameters with the same billet weight, the profile exit speed can increase significantly. It is anticipated that using 8-inch and 9-inch billets instead of 7-inch billets of the same weight, the profile speed can be increased by 18 percent and 25 percent, respectively, before the maximum exit temperature of 1080°F is achieved.

Table 1. Simple factorial design: two factors and two levels with one center point, and FE-predicted loads and temperatures.

Billet Length [inch]	**Billet Diameter [inch]**	Extrusion Load [ton]	Load on Container [ton]	Load on die [ton]	Dummy Pressure [ksi]	Maximum Temperature at exit [°F]	Average Temperature at Exit [°F]
32	**7**	1778	602	1176	83	1069	1042
32	**9**	2627	716	1911	76	1060	1033
64	**7**	2271	1172	1099	106	1080	1054
64	**9**	3304	1444	1860	96	1063	1036
48	**8**	2460	991	1469	89	1067	1042

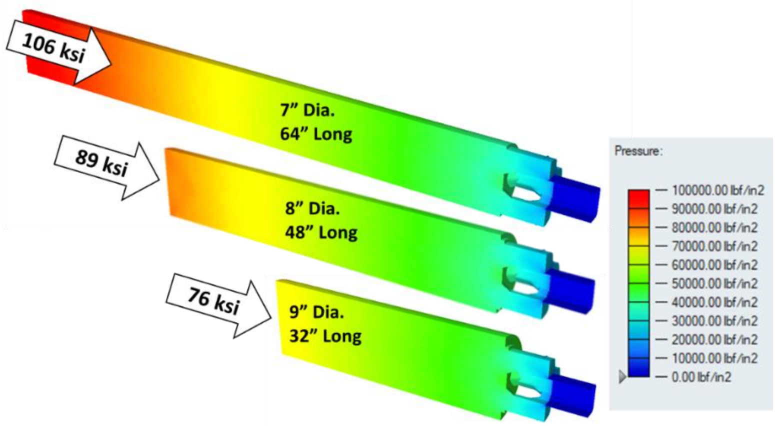


Figure 2. Effect of billet dimensions on pressure distribution for constant profile velocity.

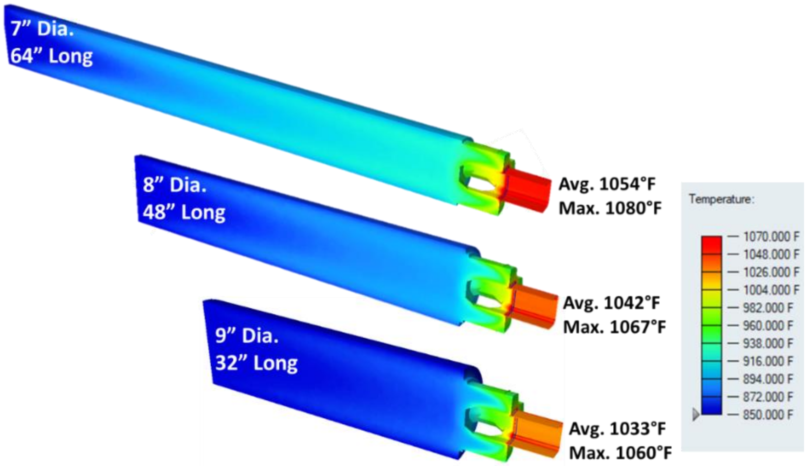


Figure 3. Effect of billet dimensions on exit temperature for constant profile velocity.

A regression method is used to fit equations for loads and exit temperatures in terms of billet diameter and length. The effect of mixed parameter (billet diameter billet length) is also considered, which represents the billet/container contact area. Figure 4 shows the fitted surface on the model predicted values for extrusion load and average exit temperature. Both surfaces show a good fit with R-sq. value more than 99.9 percent, meaning that the fitted surface can be used with a good level of accuracy to interpolate responses for new points in the range.

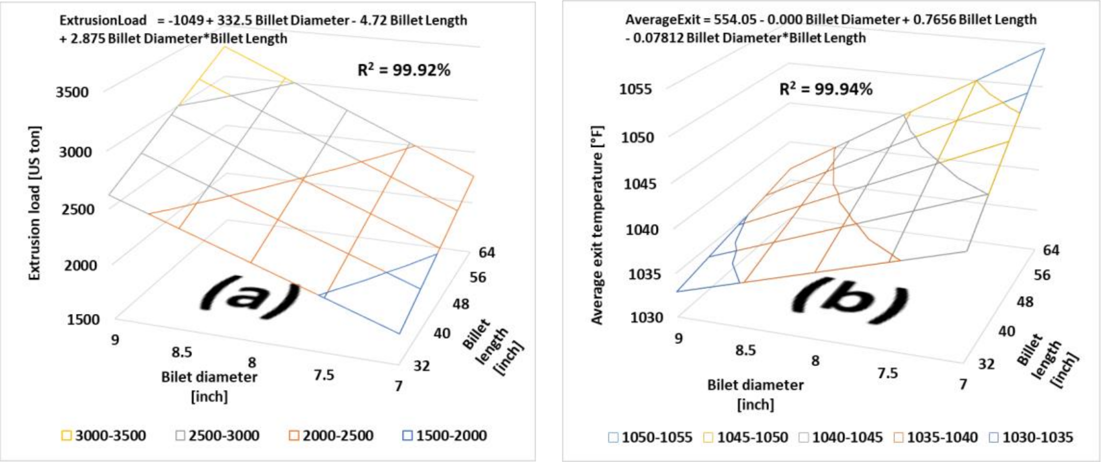


Figure 4. Regression fitting results for extrusion load (left), and average exit temperature (right).

Simulation predicted loads and temperatures are statistically analyzed and the standardized effect of billet dimensions on predicted responses are calculated. The standardized effect is the difference of means divided by standard deviation. [6] In Figure 5, the relative significance of billet geometry factors (billet diameter, billet length, and length diameter) are evaluated by comparing the standardized effects of these parameters. It can be concluded that in this study, the extrusion load and portion of load on die set are more affected by billet diameter than billet length, but in contrast, the pressure on the dummy face and portion of load on container are more affected by billet length, rather than by billet diameter. The standardized values show that in general, the billet diameter determines the load on the die set, while billet length has a minor effect on it, which happens to be an indirect effect referred to in Table 1.

Although the billet length has the largest effect on the portion of load on the container, the billet diameter is also a significant parameter determining the container load, which has a direct effect as billet length. Both maximum and average temperatures are showing the same order of effects, such that the billet diameter affects them more than billet length.

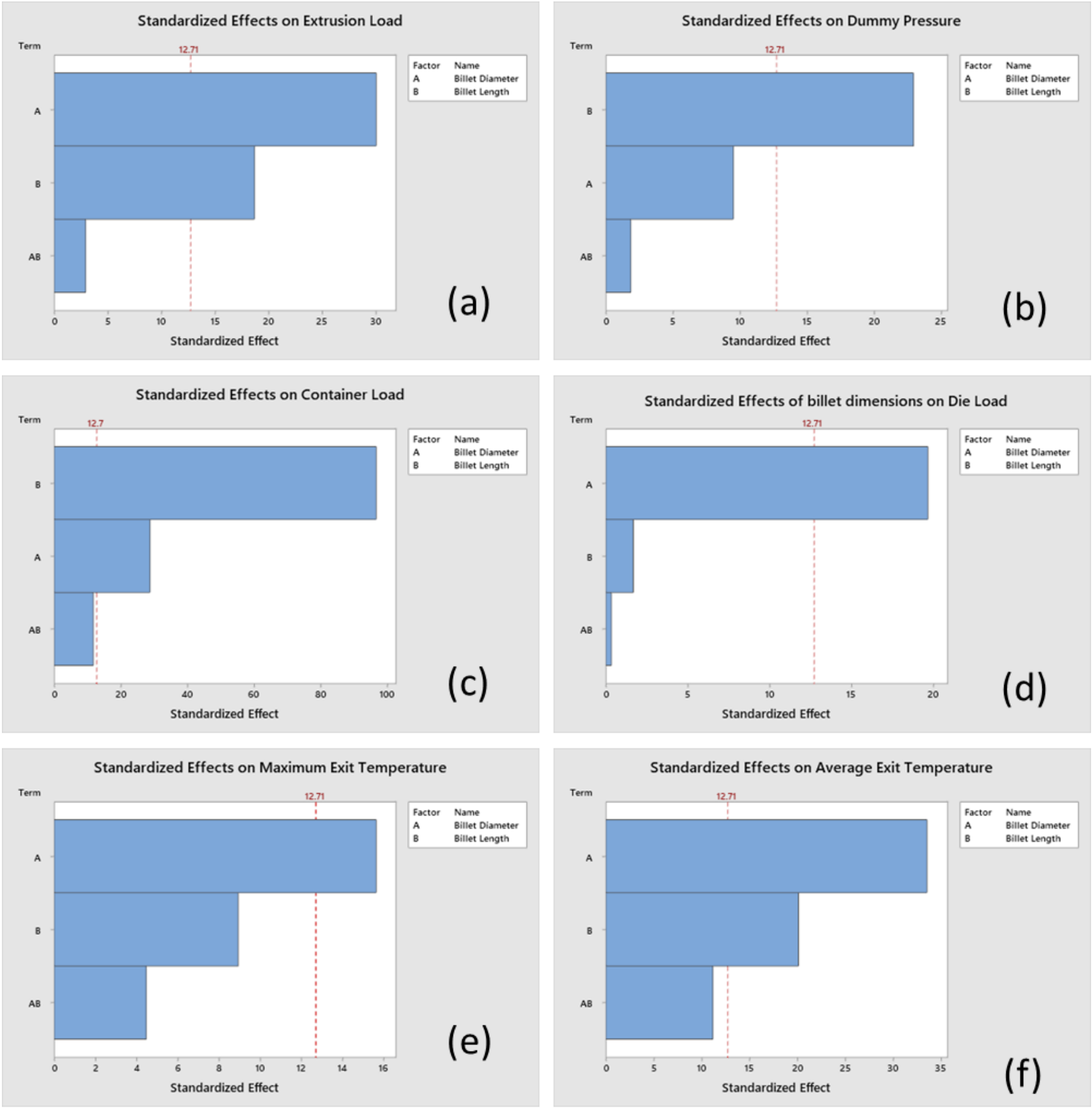


Figure 5. Standardized effects of billet diameter: a) billet length; and b)-f) mixed factor (A*B) on load and temperature responses.

Short versus Long Billets

If we want to compare the breakthrough pressure of short billet versus long billet, one of the formulas to use would be: [7]

Pressure = A log (Extrusion Ratio) + B (alloy shear stress * liner surface area)

The first term represents the part of the force that goes to reducing the billet to the profile or basically, the portion of load on the die set. The second term calculates the force to overcome shearing of the billet as the metal moves through the container. With the complication of the temperature rise through the heat of deformation, this is more accurately calculated by FE modeling.

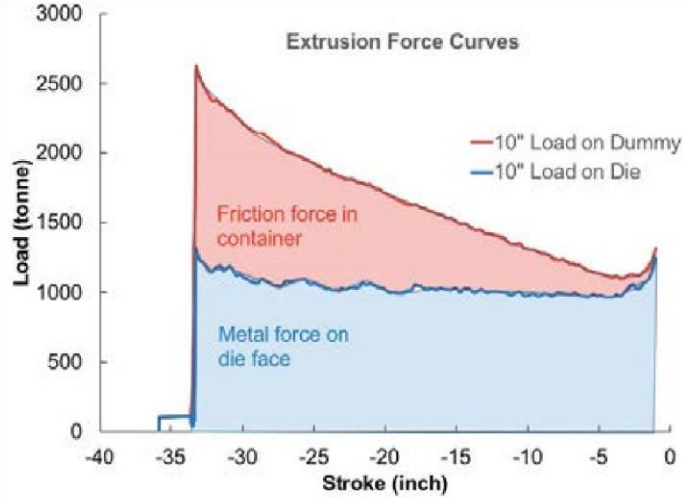
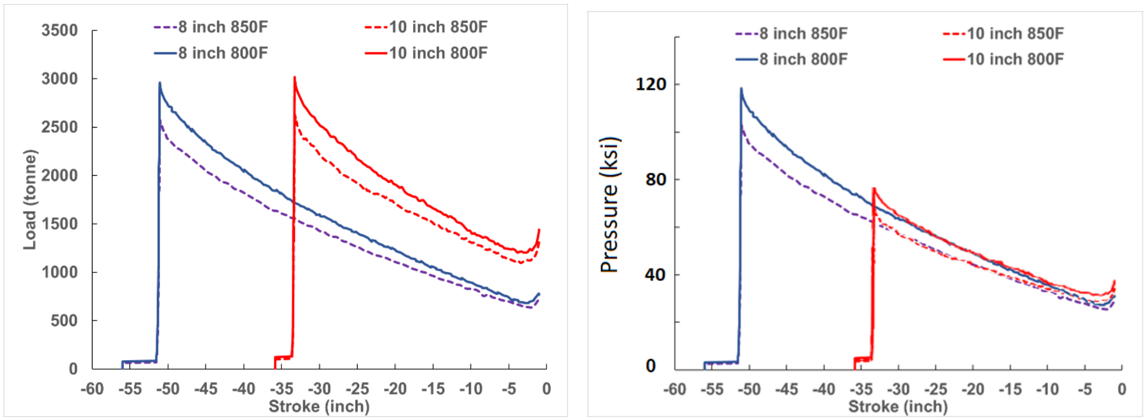


Figure 6. Showing the forces on the dummy block and die face, the red area shows the work creating friction heat transferred to the container; the blue, the work creating heat transferred to the die. **[8]**

Previous work addressed the effect of billet geometry on extrusion productivity. [8] It considered whether or not it is better to extrude billets with a length of over seven times their diameter, rather than five times. To do this, experiments were conducted using an 8-inch x 56-inch billet with an 8.375-inch diameter container and a 10-inch x 35.84-inch billet with a 10.375-inch diameter container. The results of the experiments were extremely interesting and are summarized in Figure 7. Figure 7a shows extrusion load (or dummy block loads) for the two billet diameters (8-inch and 10-inch) and two temperatures. In brief, with a fixed alloy, billet weight, die, and extrusion speed, the breakthrough loads are almost identical. Figure 7b shows the dummy block face pressure for the two billet diameters. The maximum dummy block face pressure with an 8-inch-long billet at 800°F (~120ksi) is about 50 percent more than 10-inch short billet with the same volume (~80ksi). This huge difference will affect the durability of the dummy block, as well as the container and stem.

The mechanical work to extrude the 8-inch billet is about 35 percent more than the 10-inch billet (~20MJ for the 8-inch billet versus ~15MJ for the 10-inch billet at 800°F); that translates to 35 percent more energy consumption. On the other hand, there is a large difference in the specific pressure with the 8-inch billet, which makes the dummy block and container design difficult. This might suggest that a simple solution is to use a larger diameter billet.



(a) load (b) pressure

Figure 7. a) Dummy block loads for different billet diameters and temperatures; and b) die bearing temperature for the two billet sizes extruded at 800°F.

In general, the previous research on billet geometry showed that it is not necessarily better to extrude longer billets in the hope of achieving higher productivity. Rather, the optimum billet length is determined by the product mix, the extrusion weight, and the profile circle size. Furthermore, longer billets tended to require higher pressure on the dummy block and in the container, higher ram movement with an associated higher oil flow and problems with upset and front-to-back variation in dimension. With a lower breakthrough pressure required, shorter billets can be heated to a lower temperature, providing a greater potential for increased extrusion speeds.

Figure 8 shows FE simulation results showing the effect of billet diameter on extrusion loads, while keeping the profile speed and billet weight as constants. The portion of load on container and die are separated to see the effect of billet dimensions on them. Although the billet length and ram speed are adjusted to get the same billet weight and profile speed, the extrusion load increases with increasing the billet diameter.

The portion of load on die set increases with billet diameter, due to more work spent on reduction of area, but the load on container is decreasing due to significant decrease of billet/container contact surface area.

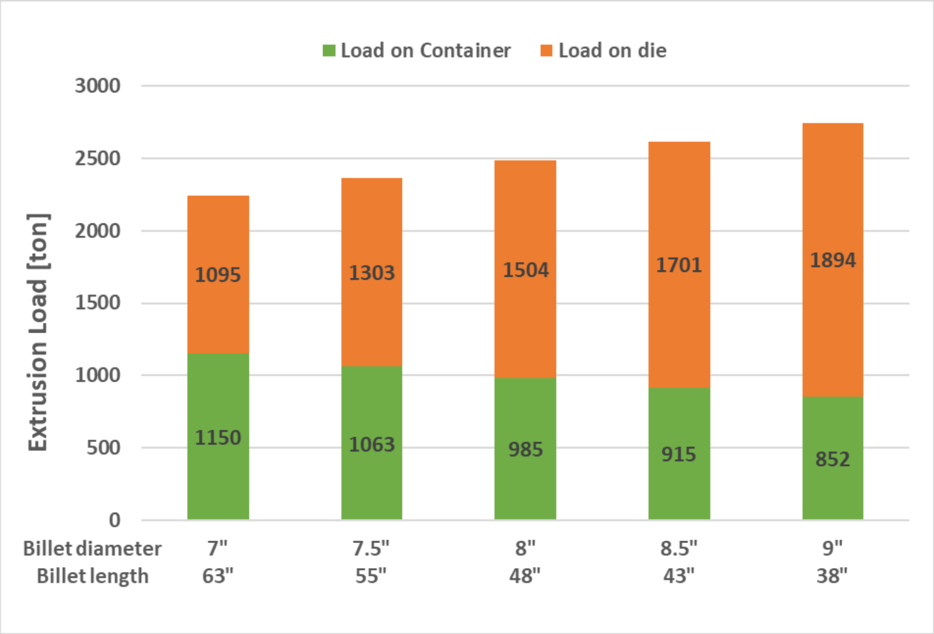


Figure 8. Effect of billet dimensions on extrusion loads for constant profile velocity and billet weight.

Although the maximum load on the dummy block increases with billet diameter, model predictions presented in Figure 9 show that the pressure at the dummy block surface decreases significantly when increasing the billet diameter. The reason is the pressure drop from the combination of increasing surface area and decreasing ram speed and billet length. The profile exit temperature shows the same trend with billet diameter. The difference between average and maximum exit temperature increases with the billet diameter, but it seems to plateau with increasing billet diameter.

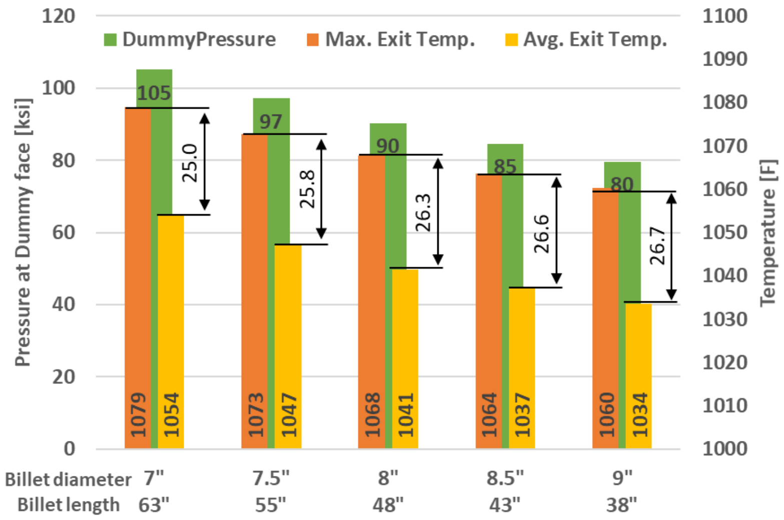
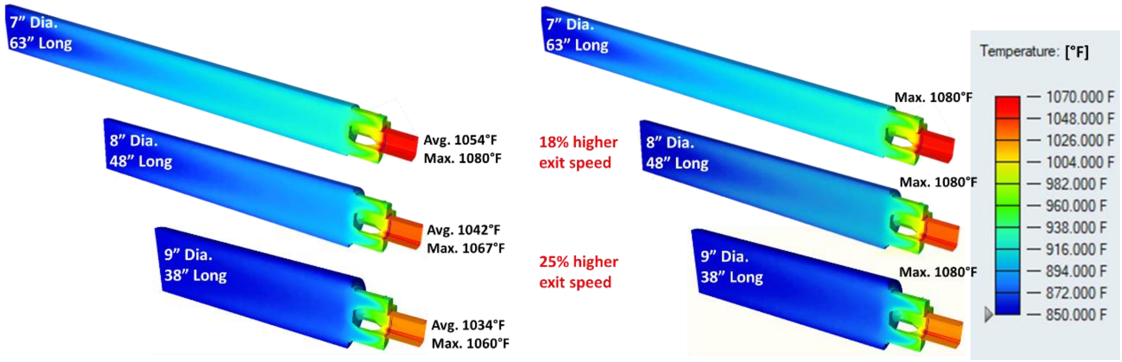


Figure 9. Effect of billet dimensions on pressure at the dummy face, and profile exit temperature for profile velocity and billet weight.

Figure 10 compares billets of the same weight, but with different diameters. In Figure 10b, exit speed is adjusted until the same exit temperature is achieved. As observed, with increasing the billet diameter from seven inches to nine inches, the exit speed can be improved by 25 percent, while maintaining the exit temperature.



(a) (b)

Figure 10. Productivity improvement with increasing billet diameter, but constant billet weight and exit temperature.

Pressure on Dummy Blocks and Dummy Block Design

Normally the dummy block is made of H13 steel, due to its high tensile strength and toughness at extrusion temperature.[9] One alternative is to use a better material for this application, such as Tuff Temper, which was developed to handle this situation. Comparative properties are shown in **Table 2**. The impact toughness is also higher than H13, which provides good thermal shock resistance. Tuff Temper that is heat treated to 48HRc has the same or better toughness than H13. The impact toughness of H13 is about 7ft-lbs and for re-melted super-clean H13, it is about 10ft-lbs, and the impact toughness of Tuff Temper is about 10ft-lbs.

The larger elastic modulus in TuffTemp steel makes it more resistant to elastic deformation, so that the TuffTemp dummy block would expend less than an H13 dummy block with the same geometry. On the other hand, for Tuff Temper, the ratio of yield stress to elastic modulus (yield/modulus) that determines the amount of deformation before yielding, is five percent less than for H13.

Table 2. Mechanical properties of H13 and Tuff Temper.

Materials	UTS (ksi)	0.2% Yield (ksi)	Modulus (ksi)
H13	184.6	156.8	25,800
Tuff Temper	196.3	165.5	28,500

The pressure at the dummy block face determines the level of stress and deformation in the dummy block and stem. Figure 11 shows how the stress would decrease inside the dummy block and stem with increasing billet diameter.

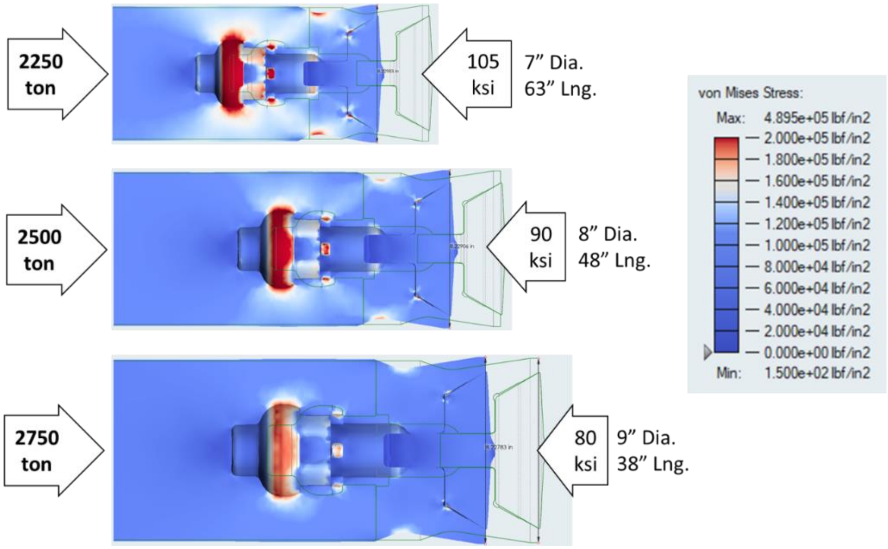


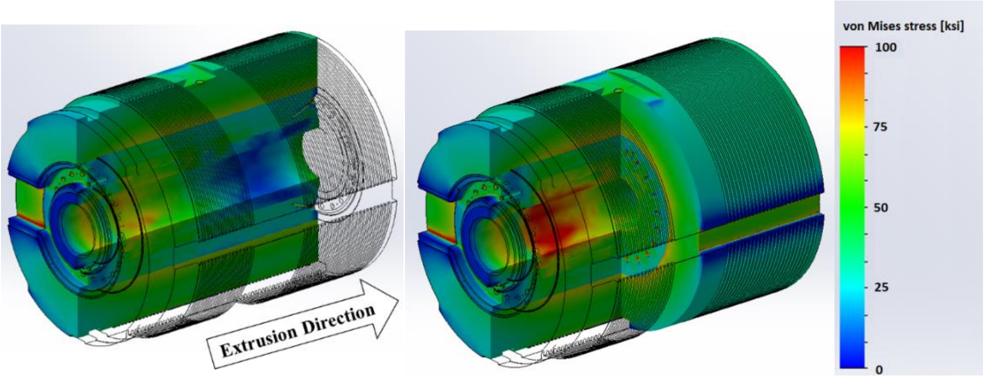
Figure 11. Stress distribution in the dummy block and stem tip changes with billet dimensions (keeping the billet weight and profile speed constant).

Aluminum Skin Thickness

One problem that has occurred with longer billets is the difficulty in designing a dummy block that works. This is because the force varies so dramatically from front to back, perhaps starting with a specific pressure of 120ksi reducing to 30ksi. Since the expansion of the dummy block solely relies on pressure, this becomes an extremely difficult problem if the objective is a uniform thin skull on the liner wall. If the skull varies in thickness front-to-back, then quality and recovery will suffer. A lower specific pressure with the 10-inch shorter billet is a huge advantage for good functioning of the block.

Container Design for Longer Billets

The container under extrusion pressure acts as a thick cylinder with internal pressure. Extrusion pressure is at maximum at breakthrough and reduces through the extrusion cycle by as much as 50 percent. The stress built up is highest near the liner inner diameter (ID) surface, and lowest near the container outer diameter (OD) surface (Figure 12). Figure 12 shows the stress distribution in a three-piece container for two different dummy block face pressures of 100ksi and 120ksi.



(a) 100ksi (b) 120ksi

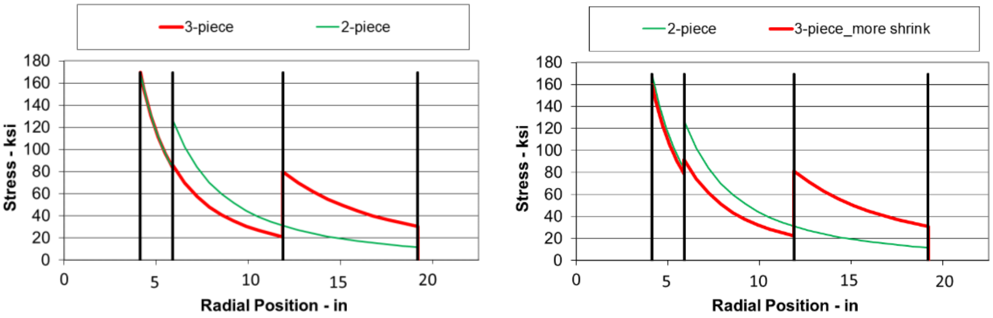
Figure 12. Stress distribution in a 10-inch three-piece container with different dummy block face pressure; a) 100ksi; and b) 120ksi.

With longer billets there is more heat generated inside the container, so that there is a need for faster heat dissipation inside the container. One method is to use more thermally conductive steels, such as ConDuct steel with 75 percent more thermal conductivity than H13, [10] which is also less expensive and tougher than H13. The downside could be that ConDuct steel is softer than H13 (lower yield stress and UTS), but unless extruding with very high face pressures shown in Figure 12b (i.e., extrusion of long billets of hard alloys), using ConDuct sub-liner should not cause a problem, as the sub-liner in a three-piece container is often under much lower stresses than the liner.

The advantage of more conductive material in the container for better heat dissipation capability was discussed in a previous publication. [11] In contrast, during the extrusion of hard aluminum alloys, such as AA7075, the ram speed is so slow, such that the heat dissipation rate is much more than the rate of heat generation by the deforming billet. In this case using H13 sub-liner with lower conductivity can help with preserving the liner temperature, and at the same time using stronger H13 material provides more support to the liner, which is needed during the extrusion of hard alloys.

With a three-piece container versus a two-piece container and applying a shrink-fit between the sub-liner and body, the pressure at the ID of the sub-liner can be reduced from 120ksi to 80ksi (Figure 13a). This makes it safe to use less-strong, more conductive ConDuct steel. Due to shrink-fit between sub-liner and body, the stress level in the body would increase, compared to a two-piece container, but the stress level is not high at this area, and so there is no need for ultra-high-strength material for the body. As a result, the H13 body can also be replaced with ConDuct steel.

Longer billets result in more pressure accumulated inside the container. With increasing the shrink between liner and sub-liner, stress inside the liner can be reduced (see Figure 13b). This extra shrink will slightly add to the stress in the sub-liner, but the sub-liner is already under good support from the body.



(a) **(b)**

Figure 13. Stress distribution along the radius: two-piece vs. three-piece container: a) same shrink at liner OD; and b) three-piece container has more shrink at liner OD (0.2 percent vs. 0.16 percent).

Billet Upset

Both billet dimensions will not buckle under normal upsetting conditions. However, upset with the constraints of the liner wall can change this. Previous work on billet upset reported at ET 2004 [12] shows that the billet upsets first in the center of the length (irrespective of even a large temperature taper), then moves backwards to the stem, and lastly upsets in the die end. During upset, the distance the billet has to move is 4.9 inches for the 8-inch, and 2.54 inches for the 10-inch. The volume of air that needs to be removed is 270 cubic inches and 210 cubic inches, respectively. Removing all air is far more difficult with the long billet, so great care must be taken with controlling the burp distance or burp pressure. With very long billets (with long length-to-diameter ratios), the completion of upset is extremely difficult, to the extent that in some situations, extrusion can start before the front end is fully upset. This could well impact skin flow into the die on the front end. Front-loading presses with the billet held central in the liner during upset perform better in this respect.

Metal Flow – The Impact of Die Design

In extrusion, there is a significant difference in flow between the outside and center of the billet. [13] This is something the die designer must account for, especially when the die apertures, ports, or pockets feeding the die profiles approach the liner wall. For a specific profile, this difference increases in proportion to the upset billet length. One can expect larger differences in flow between the front and back of the extrusion with a long billet, rather than a short billet. Of course, the circle size on the 7-inch billet will be more restrictive to profiles than the 9-inch billet. On the other hand, the increased die cost with dies for a 9-inch billet is going to be higher.

Longer Butt for Coring

The standard allowance to ensure billet skin or coring does not enter the profile is to take 12 to 14 percent of the billet weight as scrap. [14] The longer the billet, the longer the butt scrap. There are two options for dealing with this scrap. The first is to stop extruding when the butt length is 14 percent of the billet, which naturally means a very long butt and a very challenging job to achieve a clean butt shear without stripping metal out of the pockets of the die. This will increase the amount of blistering. The other choice is to extrude down to a butt thickness of one or two inches, which means an excessive amount of contamination in the die and a lot of back-end extrusion scrap; the longer the billet, the worse the situation.

SUMMARY AND CONCLUSIONS

Assuming we are extruding under ideal conditions, that is with the minimum billet temperature the press can push a reasonable specific pressure on the dummy block, and achieving the maximum speed with satisfactory quality, any increase in billet weight will require an increase in billet temperature and a reduction in extrusion speed. Depending on the product (heavy profiles, special alloys, coiled products, etc.), this could still be beneficial to recovery and productivity. However, whatever the reason to increase billet weight, the trend today seems to be to increase billet length. Such a change adds complications to different parts of the extrusion process, such as both container and dummy block design for high specific pressures, front-to-back dimensional changes, poor metal flow, scrap allowances, and others. It is suggested that caution should be taken when following this approach.

Our calculations using the extrusion conditions reported in this paper show that the effect of increasing billet weight by increasing billet diameter has an advantage to that achieved by increasing billet diameter. In fact, the problems created by long billets, such as slower achievable speeds, higher dummy block pressure, and more front-to-back variation in liner skin thickness, suggest that it is better to increase billet diameter.

- With maintaining the exit speed and billet weight, using a thicker billet would decrease the exit temperature and dummy block face pressure, but would slightly increase the peak load

- With maintaining the exit speed, extrusion load and exit temperature are more sensitive to billet diameter, while dummy block face pressure is more sensitive to billet length
- For the same exit speed and billet weight, extrusion of an 8-inch billet would consume about 35 percent more energy than a 10-inch billet
- Using a larger billet diameter would decrease the stress on the die-end face of the container
- Temperature variance range at the cross section of extrudate when exiting the die increases slightly with increasing the billet diameter, but the varying range reaches a plateau at a billet diameter of 8.5 and above
- Using longer billets may decrease the life of the dummy block due to excessive pressure
- The quality and recovery may degrade for longer billets, due to large variance of aluminum skin thickness from front to back
- Using a three-piece container (versus a two-piece container) with a proper shrink-fit can be a good solution to decrease the stress on the liner during extrusion of long billets.

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