# Extrusion Productivity:  Ram Speed/Die Design/Container

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**ABSTRACT –** Often, we see extruders who are producing very similar profiles with conventional die designs with well-known alloys and all that they can do is guess based on previous performance and experience.  Ram speeds are often very different.  Performance and productivity become a measure of confidence rather than scientifically based numbers.  Our hope is that first we can predict maximum ram speed based on the current billet, available press load and tooling, in particular the container design and materials and the die parameters.  Then, we can suggest to extruders to use the right container design and material, container set temperatures and billet temperatures to further improve their productivity.  In this paper a combination of statistical design of experiments, finite element simulation, regression analysis is used to find the maximum ram speed (maximum productivity) for any given combination of process parameters by looking at the effect of those parameters on exit temperature and extrusion loads.  Then the optimized combination is found within the defined range of parameters.  Several parameters are considered including container set temperature and taper, container conductivity, outside cooling rate of the container, billet preheat, billet dimensions and die design.  The results show that the optimum productivity can be achieved with better cooling and container conductivity, larger billet dimensions and easy to push die design. In the optimum case both exit temperature and extrusion load are at the maximum set limit.  It is interesting that the lowest productivity is achieved with the same combination of parameters except with a hard to push die design where the press load capacity is the limit and extrusion exit temperature is far below the defined limit.  With a conservative process parameters such as insulated container, low conductivity (high strength) container, short billet and hard to push die, the optimum productivity is 25 percent less than the global optimum, but the worst productivity with a conservative recipe is most probably higher than the global minimum.

## INTRODUCTION

Aluminum extrusion productivity can be measured in many ways—billets per shift, net pounds per hour, etc.[1]  These values are a useful measure of how an extruder is performing, but they do not provide a guide as to how to continuously improve.  It does not identify an operation's weak spots or the areas that should be worked on.  At its basis, gross productivity is simply the product of upset billet weight, ram speed, and the percentage of the time the ram is moving.  When multiplied by the percentage of the production that is sold (recovery), this gives net productivity.

One method for considering productivity is through a Billet Cycle Chart (or the Seconds per Billet Chart), an interesting approach developed by Alcan in the 1970s.  Using this chart (Figure 1), all the time that the press has been manned (time scheduled to operate, the last shift, last week, last year) can be added together and divided by the number of billets extruded in order to identify the average number of seconds it takes to extrude each billet.  This is a simple way to determine how time is managed in an extrusion operation—the time the press is manned and available for production, how often it is producing, how much of this time the press is under pressure with the ram moving, how much of the time the press is sitting waiting.  In other words, it can help to figure out what is wasted dead time.  With this information, an operation can look at ways to improve and increase performance.

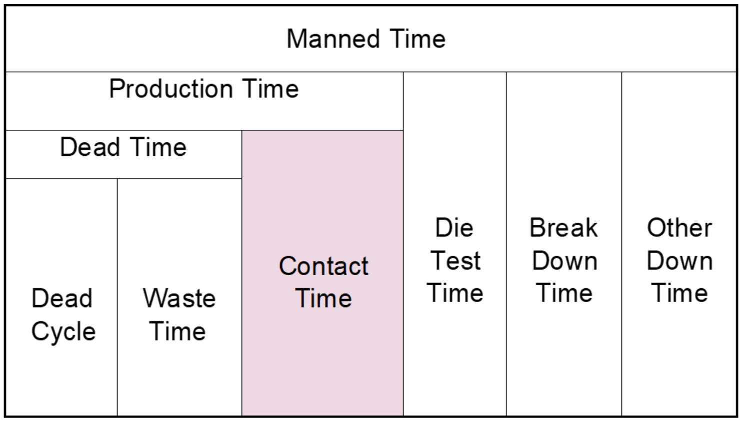


**Figure 1.** Billet cycle. [1]

Dead time can be a serious problem and it not only represents the press dead cycle, but also includes burp cycle, die changes, and many other minor stoppages. Attention to detail in an operation should reduce these kinds of stoppages. Ultimately, the main factor that affects productivity is how to reduce the live cycle time or contact time, in other words, how high can an extruder make the ram speed. It can be misleading to pay too much attention to contact utilization (percentage of the total cycle time that is live). A high contact utilization may cause an efficiency but can also indicate a low extrusion speed.

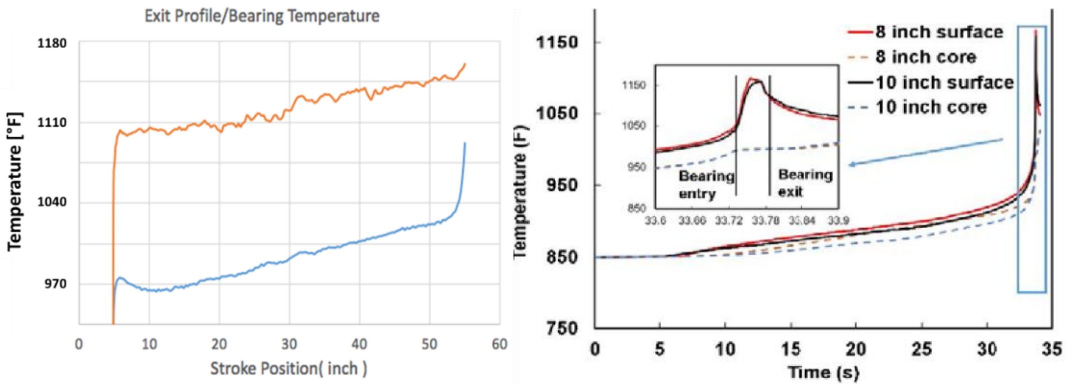
Most extruders know from experience the maximum speed at which they can safely extrude a certain profile using a certain die, and still produce the required quality. For example, they understand that 6061 cannot be extruded as fast as 6063 that hollows run slower that solids and they understand shape complexity and how die design is key to speed. But all this knowledge is empirical, rather than scientific.

Based on previous performance and experience, extruders who produce profiles in similar shapes with conventional die designs and well-known alloys often guess at the ideal ram speed. However, ram speeds tend to vary, so performance and productivity become a measure of operator confidence, rather than scientifically based numerical models. The aim of this series of articles is to determine a means to predict maximum ram speed based on the current billet, available press load, and tooling (in particular, the container design and materials and the die parameters). Then, this information can be provided to extruders enabling them to use the right container design and material, container set temperatures, and billet temperatures to further improve their productivity.

## EXTRUSION EXIT TEMPERATURE

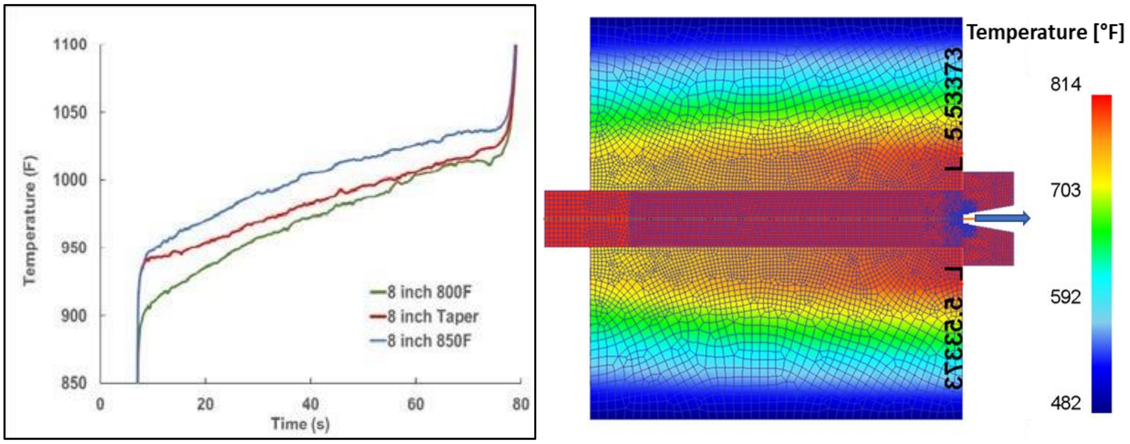
Exit temperature has always been the main monitored parameter during the extrusion and the operator always makes close attention to avoid exceeding the critical temperatures to keep a good extrusion quality. But modeling and experimental studies have shown that the temperature readings from a pyrometer do not necessarily reflect the actual temperatures experienced across the section of the extruded profile. [2] The reason is that the temperature changes are too fast in deformation zone, through the bearing and immediately after die exit and on the other hand, due to different deformation and friction conditions, the temperature history is not the same at different locations across the profile cross-section.

Figure 2a shows a typical model predicted temperature history at the bearing surface compared to the temperature at the center of the solid rod while exiting the die. The difference will equilibrate immediately after the profile exits the die (within e few seconds). Figure 2b shows how fast the temperature would change at the deformation zone. It is almost impossible to capture such a fast change in temperature experimentally at the surface of extrusion so that modeling seems to be the only tool to estimate this change. Modeling of the effect of billet/container temperature differential is illustrated in Figure 3a, which shows the die bearing temperature with an 8-inch billet and 8.357-inch container both at 800°F and 850°F, as well as an 850°F billet with an 800°F container.



**(a)** **(b)**

**Figure 2.** a) The temperature at the die bearing from front to back (upper) and the core of the profile (lower); and b) The temperature history at the surface and center of an extruded bar resulting from deformation in the container and through the die.



**(a)** **(b)**

**Figure 3.** a) The effect of container taper on temperature history at die bearing; and b) Extrusion model with 72°F tapered container.

A previous study was performed to investigate the effect of container-related parameters such as container set temperature, container taper and container conductivity on extrusion productivity [3] where billet geometry was ignored. Instead, the objective was to study what happens inside the container before the metal reaches the die in order to provide better parameters for predicting ram speed. Table 1 shows the variables and their levels that were studied. Two levels of steel conductivity were studied, comparing H13 and ConDuct steel with conductivities of 24W/mK and 42W/mK, respectively. The decision to include container material conductivity was based on the theory that heat extraction from the deformation zone can be improved with more conductive tooling.

**Table 1.** Five variables and their levels.

| Code | Variables | Level 1 | Level 2 | Level 3 |
|---|---|---|---|---|
| **A** | Container Conductivity (W/mK) | 24 | 42 | ----- |
| **B** | Billet Temperature (°F) | 800 | 850 | 900 |
| **C** | Ram speed (in/min) | 27 | 34 | 41 |
| **D** | Container set Temperature (°F) | 750 | 800 | 850 |
| **E** | Container Taper (°F) | 0 | 70 | 140 |

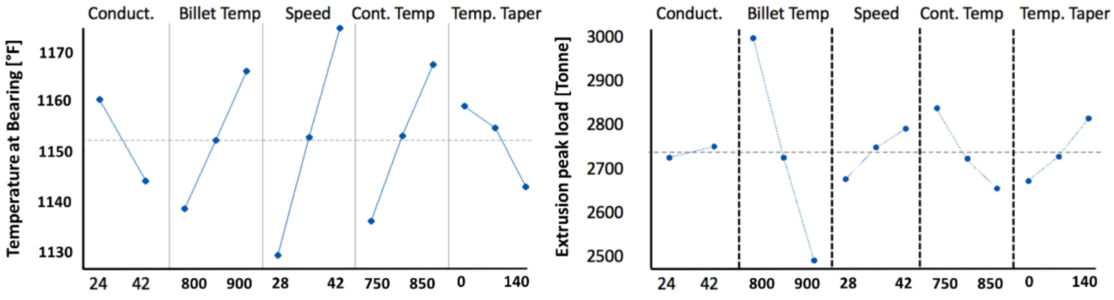
An L18 Taguchi design of experiments [4] was used to generate 18 combinations of these five variables. Then each of 18 cases was modeled using the finite element method (FEM). For simplification, a 2D axisymmetric extrusion model was developed with an 8-inch billet and 1.275-inch diameter solid round bar extrusion profile. Figure 4 represents statistical analysis results for the main effect of process parameters on temperature at the bearing surface and peak extrusion load.

The main effects of each of the five independent variables on peak extrusion load (Figure 4a) can be summarized as follows:

- Increasing the ram speed from 11.7mm/sec to 17.6mm/sec increases the breakthrough load by four percent
- Reducing the billet temperature by 100°F from 900°F to 800°F increases load from 2,440 tons to 2,990 tons (just over 20 percent)
- Reducing the container temperature by 100°F from 900°F to 800°F increases the load by seven percent
- Cooling the container back end by 144°F increases the load by five percent
- Increasing thermal conductivity of the container from 24W/mK to 42W/mK (H13 to ConDuct) increases the load by less than one percent.

The die bearing temperature (Figure 4b) can be summarized as follows:

- Increasing the ram speed from 28in/min to 42in/min increases die temperature by 40°F
- Reducing the billet temperature by 100°F from 900°F to 800°F reduces die temperature by 25°F
- Reducing the container temperature by 100°F from 850°F to 750°F reduces the die temperature by 29°F
- Cooling the container back end by 140°F reduces die temperature by less than 20°F
- Increasing the thermal conductivity of the container from 24W/mK to 42W/mK (H13 to ConDuct) cools the die by 7°C—a good benefit with no negative effects.



(a) (b)

**Figure 4.** Main effect of studied process parameters on a) Die bearing temperature; and b) Extrusion load.

The regression analysis of the breakthrough load and die bearing temperature in terms of the five variables is given in Equations 1 and 2:

Peak Extrusion Load [ton] = 8504 – 1.51W/mK Conductivity – 5.456°F Billet Temp. + 9.04 in/min Ram Speed – 1.969°F Container Temp. + 1.073°F Container Taper (1)

Die Bearing Temp. [°F] = 734.7°F – 0.323W/mK Conductivity + 0.154°F Billet Temp. + 2.872 in/min Ram Speed + 0.267°F Container Temp. – 0.132 °F Container Taper (2)

Figure 5 shows how the productivity can increase significantly with using more conductive container material, lower container temperature and proper temperature taper in container. The black line in Figure 5 represents the predicted ram speed needed to produce a temperature of 1150°F at die bearing with an H13 container (low conductivity), single zone container heating (no taper) and high temperature container. In contrast, the green dotted line shows the ram speed for 1150°F bearing temperature with a ConDuct container, lower container temperature and proper taper by multi-zone container heating system. As observed, by applying these modifications, the ram speed can be increased by 35 percent in this case.

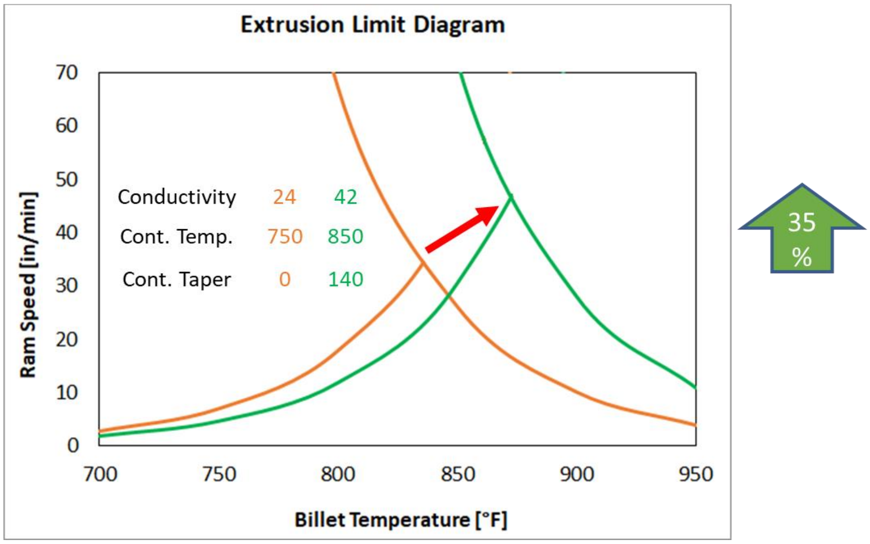


**Figure 5.** Ram speed increase as a result of better container conductivity, container temperature, and container taper.

In the current study, a combination of previous research [5, 3] is done by considering billet and container parameters as well as die design and container outside cooling rate (totally 7 parameters). In addition to exit temperature of profile the press load limit is also considered in optimization analysis. A more complex hollow profile shape is modeled using 3D FEM to capture the effect of thin features and webs. Three different porthole dies with same profile geometry and different porthole and chamber sizes were modeled to study the effect of die features on productivity.

## Die Design – Portholes and Weld Chamber

Effect of die design on productivity is studied by modeling the extrusion process with changing pocket sizes in a porthole die. Pictures and 3D CAD models of three dies studied here are shown in Figure 6. All dies produce the same profile so that they all have the same die plate and mandrel core. The varying features are sizes of potholes and weld chambers. Die 1 has regular sized portholes and welding chambers providing strong bridges and leaves some room for future modifications. Die 2 has wider portholes allowing the billet to flow easier into the die. In Die 3 the portholes are even wider than the Die 2 and weld chamber is also widened to leave more space for aluminum to flow around the bridges. The idea here is to make the flow of aluminum easier through the portholes and weld chambers so that lowering the extrusion load and exit temperature. To prove the concept, finite element simulations were performed with these three dies using HyperExtrude® FE-based software. The FE model and material flow properties are described in another paper. [6]

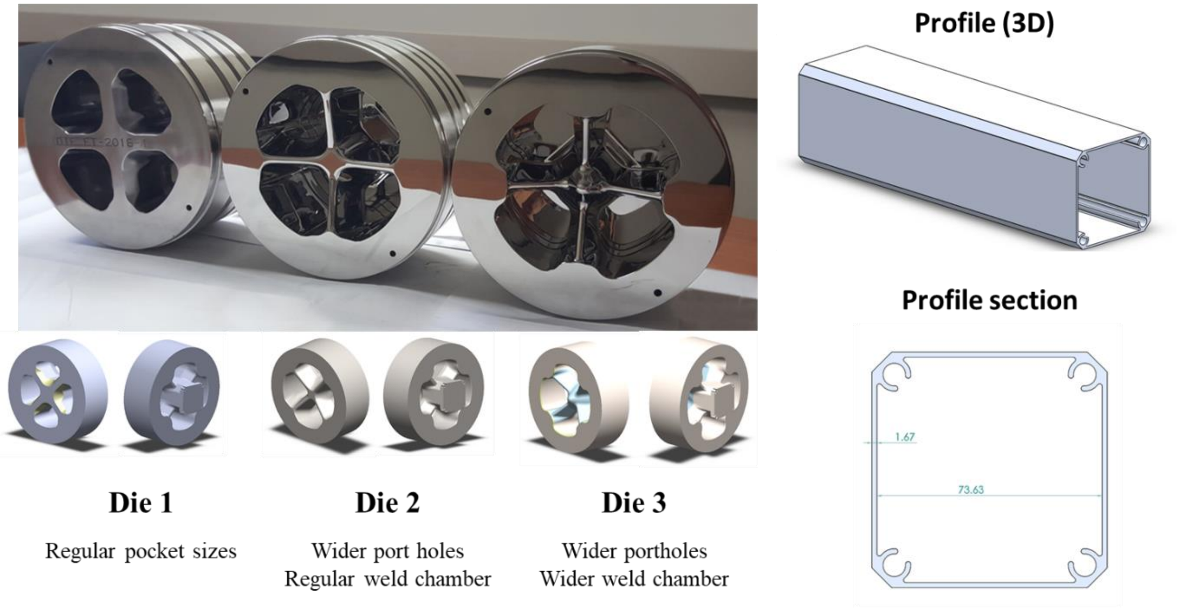
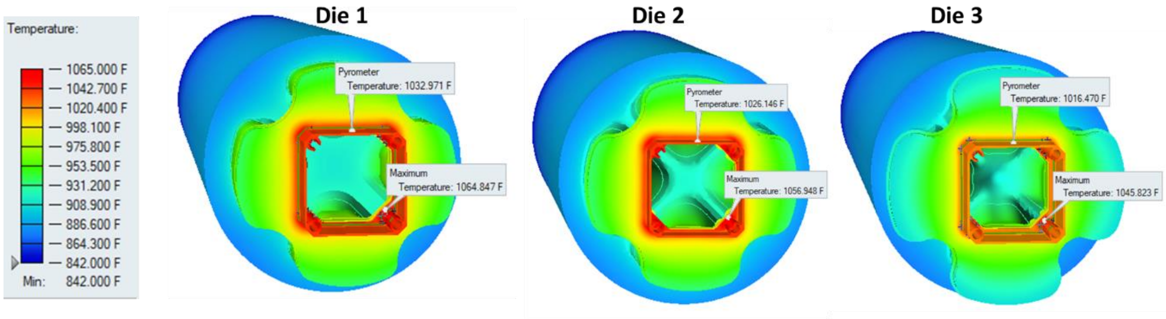


**Figure 6.** 3D presentation of three dies with different pocket sizes. All dies produce the same profile.

Figure 7 shows the comparison of temperature distribution and exit temperatures for the mentioned three dies. These simulations are done for extrusion of AA6063 billets of 8-inch diameter and 40-inch length at 842°F with a ram speed of 24in/min. The model predicted a maximum exit temperature and load decrease from Die 1 to Die 3 by 19°F and 176 tons, respectively. Based on previous research this drop in temperature is big enough to let the extrusion be performed at substantially faster speeds with minor increase in extrusion load. The simulation results for faster ram speed with Die 3 shows that the Die 3 can run 30 percent faster than Die 1 with the same maximum exit temperature (1065°F) and a slightly lower pyrometer temperature reading of 1028°F. As expected, the extrusion load just increased a minor amount of 24 tons (about one percent) with a 30 percent increase in speed.



| | Die 1 | Die 2 | Die 3 |
|---|---|---|---|
| Extrusion Load [ton] | 2080 | 2041 | 1904 |
| Maximum temp. [°F] | 1065 | 1057 | 1046 |
| Pyrometer Temp. [°F] | 1033 | 1026 | 1016 |

**Figure 7.** Model predicted temperature distribution, extrusion load, maximum exit temperature, and pyrometer readings for three dies in this study.

Model predictions in Figure 8 show the change in extrusion load and maximum exit temperature with ram speed. As expected, the sensitivity of the exit temperature and extrusion load to ram speed decreases with increasing the ram speed, reflecting the effect of strain rate on flow stress which is linear for stress versus log (strain rate). It can be concluded that in this specific case, with a ram speed increase of about two to three percent, the exit temperature would increase just about 1°F.

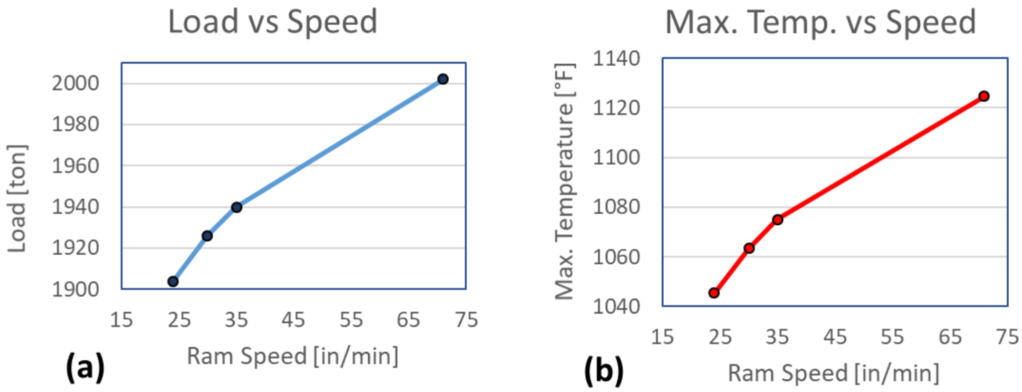


**Figure 8.** Effect of ram speed increase on extrusion load and maximum exit temperature for Die 3.

Figure 9 shows that combining the effect of die and container parameters, the ram speed can be doubled. Using dies with larger ports and chambers may increase the front scrap, but this effect on productivity is ignorable compared to productivity improvement by using these dies. This is numerically explained in another paper.[7]

| Conductivity | 24 | 42 | 42 |
|---|---|---|---|
| Container Temp. | 400 | 450 | 450 |
| Container Taper | 0 | 80 | 80 |
| Die | 1 | 1 | 3 |

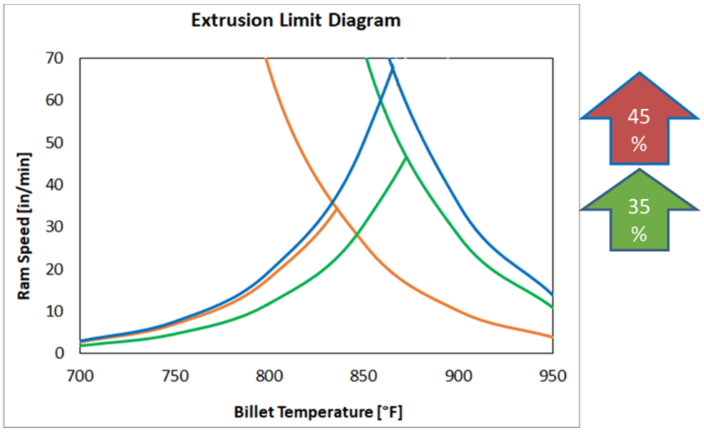


**Figure 9.** Combined effect of die and container parameters.

## Container – Material Conductivity and Outside Cooling

When the container becomes thermally saturated, it cannot dissipate the heat of deformation being generated inside the billet. In order to control the exit temperature, the operator will have to either decrease the billet preheat temperature or the ram speed. If the billet preheat temperature is already close to container temperature, decreasing the billet preheat more than that can promote *A-type* flow [8] in the billet, so that the billet skin would flow towards the die and degrade the surface of the profile. On the other hand, decreasing the ram speed would decrease the productivity. Unfortunately, there is no immediate solution for container saturation without sacrificing the quality or productivity, unless there are options for faster heat dissipation from the container such as forced air or water cooling. The best solution is to use a container with better heat dissipation capabilities, using more conductive material and proper design.

Figure 10 shows the model predicted temperature distribution and heat flux rate in a three-piece container with different designs, materials, and cooling methods. The container at the left (Number 1) has its three pieces made of H13 steel with a helical groove between sub-liner and liner that has forced air running through it for cooling. Container Number 2 has a ConDuct sub-liner and body instead of H13. The outside surface of the body has parallel grooves (fins) to produce more contact area for better cooling.

The third container is exactly the same as the second case, except it has air passing though the fins at the surface for better cooling. For all cases, the liner ID is at a constant temperature of 790°F, and heat is dissipating from the surface and sides of the container by air convection.

Although the H13 container with no fins has air cooling between the sub-liner and body, it has slightly less heat dissipation capabilities than the ConDuct container with outside fins. The ConDuct container with air-cooled outside fins has almost double the heat dissipation capability compared to other cases.

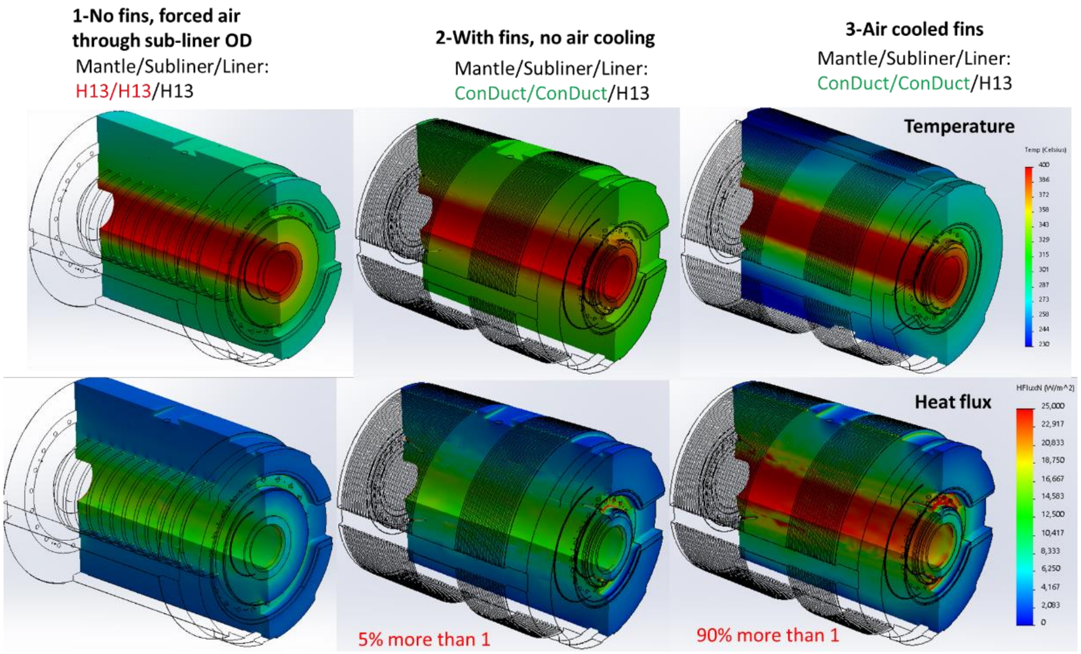


**Figure 10.** Effect of material conductivity and container cooling on the temperature distribution and heat dissipation rate in the container.

## RAM SPEED OPTIMIZATION – Container/Billet/Die Design

Ram speed is the main parameter controlling the extrusion productivity so that optimizing/maximizing the ram speed is the most effective method to maximize the productivity. A previous study [3] dealt with the effect of container-related parameters on extrusion productivity. In this study, the effect of seven different variables including the effect of billet and die parameters were also investigated. The parameters of interest and their levels are listed in Table 2. The values and ranges of each parameter were chosen based on common practice applied in industrial extrusion of 6063 aluminum alloy.

The die design is defined here as a quantitative variable and it is translated to numbers such that its value is 1, 2, and 3 for a hard to push, medium, and easy to push die, respectively.

Similar to the previous Department of Energy (DOE) study on the effect of container-related parameters, in this study Taguchi's L18 design is again used to design the experiments for this study (Table 3).

**Table 2.** List of variable parameters and levels.

| # | Code | Parameter | Level1 | Level2 | Level3 |
|---|---|---|---|---|---|
| 1 | **CC** | Container Conductivity (W/m°C) | 24 (H13) | 42 (ConDuct) | --- |
| 2 | **OC** | Outside Cooling (W/m^2°C) | 2 (Still Air) | 5 (Free Air) | 8 (Forced Air) |
| 3 | **RS** | Ram Speed (mm/s) | 3 (7in/min) | 5 (12in/min) | 7 (17in/min) |
| 4 | **BT** | Billet Temperature (°C) | 420 (788°F) | 450 (842°F) | 480 (896°F) |
| 5 | **BL** | Billet Length (in) | 28 | 32 | 36 |
| 6 | **BD** | Billet Diameter (in) | 7 | 8 | 9 |
| 7 | **DD** | Die Design | 1 (Hard) | 2 (Medium) | 3 (Easy) |

**Table 3.** Taguchi L18 design of experiments.

| C | Parameters | | | | | | | Peak Load [ton] | Max. Exit temp. [°F] |
|---|---|---|---|---|---|---|---|---|---|
| | CC | OC | RS | BT | BL | BD | DD | | |
| **1** | 24 | 2 | 7 | 790 | 28 | 7 | 1 | 1960 | 993 |
| **2** | 24 | 2 | 12 | 840 | 32 | 8 | 2 | 2285 | 1055 |
| **3** | 24 | 2 | 17 | 900 | 36 | 9 | 3 | 2678 | 1107 |
| **4** | 24 | 5 | 7 | 790 | 32 | 8 | 3 | 2384 | 989 |
| **5** | 24 | 5 | 12 | 840 | 36 | 9 | 1 | 3037 | 1069 |
| **6** | 24 | 5 | 17 | 900 | 28 | 7 | 2 | 1715 | 1072 |
| **7** | 24 | 8 | 7 | 840 | 28 | 9 | 2 | 2624 | 1013 |
| **8** | 24 | 8 | 12 | 900 | 32 | 7 | 3 | 1606 | 1034 |
| **9** | 24 | 8 | 17 | 790 | 36 | 8 | 1 | 2799 | 1061 |
| **10** | 42 | 2 | 7 | 900 | 36 | 8 | 2 | 2027 | 1037 |
| **11** | 42 | 2 | 12 | 790 | 28 | 9 | 3 | 2992 | 1018 |
| **12** | 42 | 2 | 17 | 840 | 32 | 7 | 1 | 1980 | 1070 |
| **13** | 42 | 5 | 7 | 840 | 36 | 7 | 3 | 1768 | 991 |
| **14** | 42 | 5 | 12 | 900 | 28 | 8 | 1 | 2068 | 1065 |
| **15** | 42 | 5 | 17 | 790 | 32 | 9 | 2 | 3248 | 1061 |
| **16** | 42 | 8 | 7 | 900 | 32 | 9 | 1 | 2505 | 1059 |
| **17** | 42 | 8 | 12 | 790 | 36 | 7 | 2 | 2277 | 972 |
| **18** | 42 | 8 | 17 | 840 | 28 | 8 | 3 | 2241 | 1049 |

Figure 11 and Figure 12 show the main effect of different process parameters on extrusion peak load and maximum temperature of extrudate at the die exit. As observed, the billet diameter has the biggest effect on the extrusion load, and ram speed has the largest effect on exit temperature.

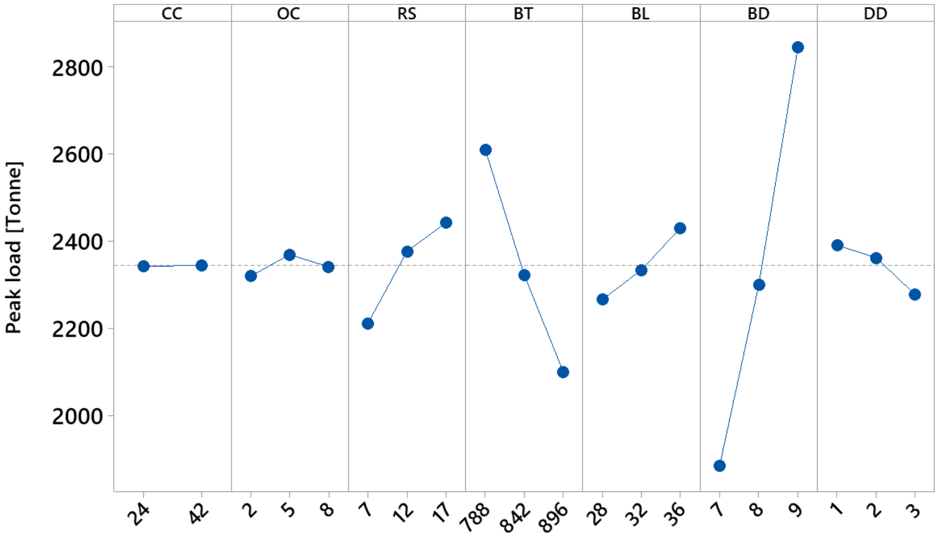


**Figure 11.** Main effects of extrusion process parameters on extrusion load and exit temperature.

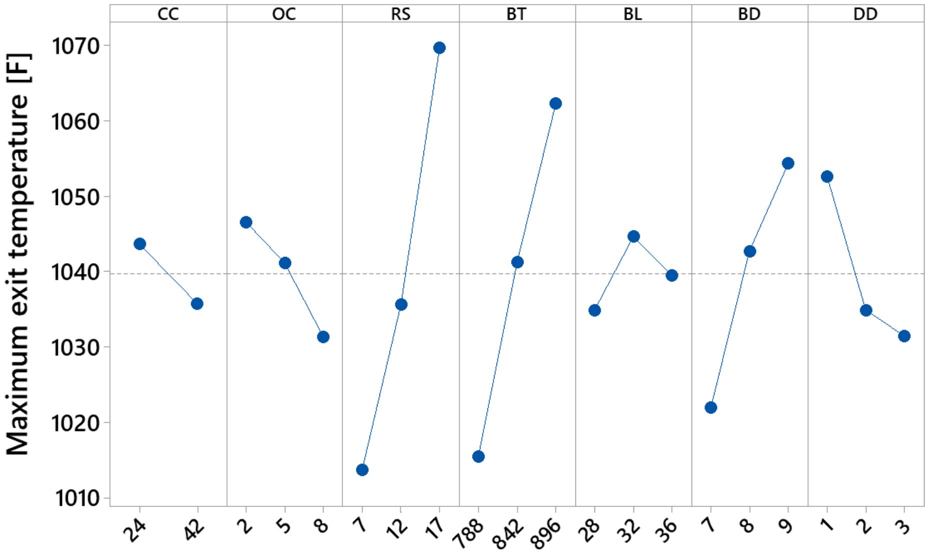
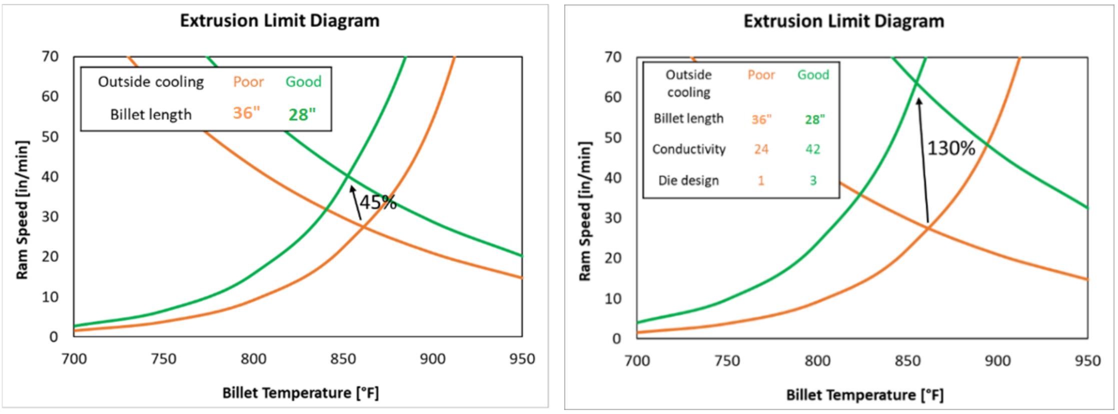


**Figure 12.** Main effects of extrusion process parameters on extrusion exit temperature.

Using regression analysis and curve fitting techniques, extrusion limit diagrams are extracted for different combinations of process parameters. Process limits used are as follows:

1. Maximum exit temperature must be below 1110°F (600°C)
2. Extrusion load cannot exceed 2500 tons (press capacity).

Figure 13 shows the effect of process parameter modification on ram speed improvement with mentioned process limits. As observed, the ram speed can be improved by more than 100 percent with suggested modifications listed in Figure 13b. Figure 13a shows the effect of outside cooling and billet length only.



**(a)** **(b)**

**Figure 13.** Effect of process parameters on extrusion limit diagram: a) Better outside cooling and shorter billet length increase ram speed limit by 45 percent; b) Combination of better outside cooling, shorter billet, more conductive container and modified die design can improve ram speed limit by more than 100 percent.

Referring to Figure 11 and Figure 12, the die design has the biggest effect on improving the ram speed or productivity. As observed, switching from Die 1 to Die 3 can decrease the extrusion load by about seven percent and at the same time, the exit temperature would decrease by about 20°F. These together would significantly move up the limit diagram curves. Container conductivity and outside cooling come next, as they have a very minor effect on extrusion load while they decrease exit temperature and open the road for increasing the ram speed. As expected, larger billet dimensions increase both load and exit temperature. With using smaller billets ram speed can be improved significantly, but the question is: does a smaller billet improve extrusion productivity or not? That is the subject that has been studied in another paper.[6]

## SUMMARY AND CONCLUSIONS

Model predictions suggest that exit temperature readings by pyrometer after the die exit may not reflect the maximum temperature at the die exit. The extruded material may experience much higher temperature in the bearing region. On the other hand, distribution of temperature at the die exit is not uniform and depending on the profile geometry, the temperature difference between coldest and hottest points of the cross-section can reach 100°F at the bearing region.

Sensitivity of extrusion load and exit temperature to several process and tooling parameters were investigated using a combination of simulation and statistical analysis, and the results of sensitivity analysis were used to extract a process limit diagram. It is concluded that container parameters such as material, temperature, taper, and outside cooling have a significant effect on process limits and using a good combination of these parameters can improve the ram speed by 35 percent. That of die design can be 45 percent improvement. At the end, combining the effect of all parameters investigated in this study, the ram speed can be improved by about 130 percent. Conclusion points, as follows:

- Extrusion surface temperature is much higher than core and dissipates rapidly; pyrometers do not tell us

- Maintaining the back of container cold (relative to the billet) is good for productivity

- External container cooling combined with good control of liner bore temperature increases temperature stability and productivity

- Small bridges and open ports increase speed

- Using more conductive material in the container increases productivity.

## ACKNOWLEDGMENTS

The authors would like to acknowledge Castool Design team and EXCO Extrusion Dies for providing CAD designs. Also, thanks to Rio Tinto Aluminium for allowing one of the authors (C. Jowett) to contribute to the paper.

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