# A Fine Balance: The Difference between Excellence and Mediocrity

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**ABSTRACT –** Extrusion management teams often ask similar questions: “We have great equipment. Why can’t our dies produce a profile within tolerance? Why can’t our die correctors get our dies running faster? Why do we struggle to achieve mechanical properties sometimes? Why is it so hard to be successful in this business?” Extrusion is a balancing act between people and technology systems; it is full of trade-offs and highly dependent on the physical realities of the tooling, equipment and processes. Excellence seldom results from doing excellent things, but rather from doing ordinary things with an excellence mindset. Certain key parameters, if left uncontrolled, will inhibit progress, irrespective of the effort put into the rest of the processes. Some extruders have cycled upwards through learning and development toward world-class results, only to drop to, or below, average industry levels. The authors use their decades of differing extrusion experience to highlight which focus areas result in performance growth or decline. It takes both technical expertise and exceptional management, working together, to succeed. The paper will NOT cover every element of an extrusion company but will provide key insights and recommended areas of focus.

## INTRODUCTION

Benchmarking procedures and the various improvements required in measurement, equipment, and processes that could potentially turn an average extruder into a Super-extruder have been widely discussed in literature,[1] but it seems that the primary beneficiaries of all this knowledge have been the Super-extruders.[2] They are the ones realizing the largest gains in productivity and profitability, while the average extruders languish behind, with only small improvements. Why is this?

### Still the Same – the Physics of Extrusion

The extrusion press cycle is still the same as it was when the original benchmarking studies were done in the early 1980s. Every extruder is faced with the identical exit temperature constraints for a particular profile and alloy. The physics of extrusion is the same, and each extruder must: extrude at nominal pressure (too low means billet is too hot, too high means extrusion is delayed); extrude in automatic cycle (reduce dead and wasted time); and must not extrude scrap (why waste valuable time producing scrap, when you can make butt large enough). If the extruder does not abide by these rules, they will either leave money on the table or go out of business.

The concept of Muda (waste) [3] is key in understanding the difference between the highest performers and the rest of the crowd. Waste needs to be identified and eliminated. Those that do this the best become the best extruders.

Waste can come in many forms:

1. Scrap is the most obvious form of waste in the extrusion process. Average extruders convert less than 80 percent of the billet to final product, while the Super-extruders manage to achieve recoveries in the mid to high 80s percent. This is achieved by a balance of attention to detail in the planning process (correct die stroke number with the correct billet length and alloy combination) together with good downstream handling to ensure the minimum amount of damage to the product. An understanding of how the wt/foot of the extrusion changes through an order is

key to facilitating the use of the minimum amount of billet to get the product we need.[4, 5] Additionally, a balanced approach to die design (especially in hollow dies) can help reduce the amount of transverse weld (charge weld) scrap to a minimum. [6]

2. Time is a valuable resource that is easily wasted. Time is essentially contact utilization — that part of the extrusion cycle where one is actually making money. The difference seen here between the average extruder and the Super-extruders is also not large, perhaps 60 percent vs. 65 percent respectively. This can range from approximately 50 to 70 percent of total cycle time in the marketplace. The wasted time is not just the dead cycle of the press, but also the downtime from full tables, breakdowns and die changes (to mention a few). A key tool here is benchmarking, and this will be discussed in more detail later.

3. Production speed. Once we have minimized the planned and unplanned process scrap, plus reduced the waste time to a minimum, then what is left is the contact cycle. That is actually the time we spend extruding. Here, the waste we need to minimize is the lost opportunity waste that comes from extruding slower than we potentially could. Here is where the Super-extruders come into their own. Ram speeds have the greatest potential variability; they can range from 7 inches/min (3mm/sec) up to 40-45 inches/min (18 or even 20mm/sec) for some 6xxx-series alloys. Here, the difference between average extruders and Super-extruders shows a bigger gap. Average extruders run speeds of 23 inches/min (9.7mm/sec), whereas Super-extruders run at 30 inches/min (12.7mm/sec) for 6063 alloys, or approximately 30 percent faster. This might appear to be the best potential for improvement for the average extruder – just crank up the ram speed and become Super-extruders too! But it is not that easy. Cranking up the ram speed is a good start, but the process is limited by alloys, dies and most importantly, by temperature. Faster ram speed generates more heat, and that heat must be dissipated. Container design/materials have a big impact here. Good die design can reduce the amount of work done getting the metal through the die and hence, reduce the amount of heat generated. Leaner alloys can achieve the same properties as the more heavily alloyed counterparts, while reducing flow stress and hence, the heat generated in the process.[7, 8] Getting the right combination of die designs alloys and process is the key to becoming a Super-extruder. However, if you want to go faster, then you need to have a well-maintained press, with excellent thermal control, excellent alignment, and excellent process control before you can use those special dies and alloys. There is waste in the alloys that are used. Poor thermal control allows some Mg and Si to form $Mg_2Si$ particles. These were once thought to be the hardening particles before the latest generation of electron optics allowed us to observe the hardening particles in the alloys. [9] There is still some debate about the exact stoichiometry of the good hardening particle, but the general opinion in the literature is coalescing around $Mg_5Si_6$. Opportunity waste occurs when alloys previously referred to as balance (2:1 Mg/Si ratio) roughly double the amount of Mg that is necessary to form hardening particles. The excess Mg that does not contribute to final properties, does have a negative impact on the flow stress of the alloy, and hence, increases pressure and temperatures unnecessarily. High-performance alloys have been developed to take advantage of this new knowledge.[10] Here is where the Super-extruders win out, not by doing extraordinary things, but by doing ordinary things extraordinarily well.

In recent years, there has been a trend toward longer containers, many of which are front loading. These have allowed the use of longer billets and shorter dead cycle times in a relatively small footprint. As the dead cycle time is still the same or shorter, the relative percentage of live cycle time has been increased with an exponential increase in contact utilization. But there are downsides to this. Although some extruders have experienced the hoped-for improvement, particularly those producing coiled products, the problem is that longer billets must overcome more friction. This results in much higher temperatures, more stresses on the dummy block, and problems with metal flow and butt shearing.[11] The only option left may be to reduce ram speeds, cancelling out any longed-for gain in productivity.

The funny thing is, the faster one goes, the faster one can go. Surface finish becomes better, and if the extra heat can be dissipated by the container, the knobs can be turned up and increase productivity and profit!

## Realities

The *perfect die* can only be used as a result of an increased knowledge of the moment of extrusion and an understanding of the effective interaction of components that support the die. These include but are not limited to mechanical and thermal press alignment, billet temperature, die temperature, and container temperature. If these are not controlled, the perfect die will require features that increase friction, cause temperatures to increase, and slow ram speed. Most die correction is temperature induced and increases friction, reducing speed and adding variability to the process.

Long billets (those more than five times diameter) require more press force to maintain the required break through pressure, which may require a three-piece container and a stronger dummy block. They may also affect metal flow, profile dimensions and butt length calculations. Longer billets produce more heat, and unless billets, containers, and dies can compensate, ram speeds will be reduced.[12. 13] The 10- to 12-second dead cycle exists, but is typically not used by Super-extruders, and can cause more downtime associated with equipment reliability. Temperature in extrusion is often not uniform. Therefore, the aim is temperature stability of the billet, container, die, and profile. The right equipment need not be the newest. Many Super-extruders do not have the newest presses and equipment.

## Bennett Numbers

Having a good overview of your process and having data to measure your progress is vital to a well-organized developmental process. Lord Kelvin once said, “When you can measure what you are speaking about, and express it in numbers, you know something about it, when you cannot express it in numbers, your knowledge is of a meager and unsatisfactory kind; it may be the beginning of knowledge, but you have scarcely, in your thoughts, advanced to the state of science.”[14] Bennett numbers refer to three benchmarking parameters that Roger Fielding described [1, 15] for benchmarking extrusion operations:

- Contact efficiency: ratio of extrusion active cycle time to total cycle time (Figure 1)
- Recovery: weight ratio of sold good extrusion to used billet material (Figure 1)
- Ram speed: indicating the extrusion speed.

How you balance these numbers has a big effect on overall productivity. One must be very careful about taking any one number by itself. With a constant dead production time and billet length, the most productive presses typically have the lowest *contact efficiency*, since extrusion time is minimized. The easiest method to increase contact efficiency is to use a longer billet, immediately extrusion time proportionate to dead time is increased. If everything else stayed the same, it may be a good decision. But if temperatures are increased, speed may be reduced and expected efficiencies not realized.

*Recovery* is important, but not at the loss of speed. Recoveries at or above 90 percent are possible, but most high-productivity presses operate low to mid 80s percent. The same can be said about ram speed. High ram speeds with exceptionally low recovery cannot be good.

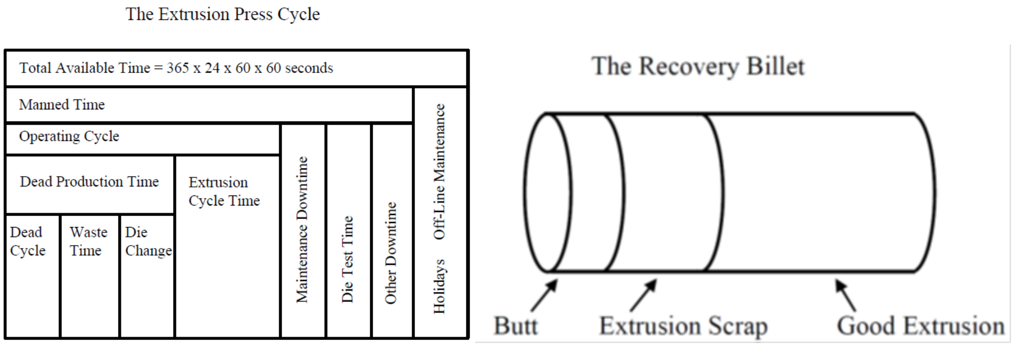


**Figure 1.** The extrusion press cycle (left); and the recovery billet (right).[15]

## FINE BALANCE CASE STUDIES

In this paper, some case studies are presented to better understand the concept of fine balance and how it can improve extrusion plant productivity.

### Material Selection

The most important material properties for extrusion tooling (i.e., container, dummy block and die) are wear resistivity, ductility, thermal conductivity, and cost. Table 1 lists these properties for some of the common materials. Proper material selection must be done to keep the balance between these properties to be able to take advantage of the maximum capacity of the machine to optimize productivity. For instance, when selecting a material for the main body of a container, it must be remembered that the main function of the container is to dissipate heat and that strength, while important, is of secondary importance. Thus, using an ultra-strong and expensive material with low thermal conductivity in a container body, when a material of adequate strength and high thermal conductivity is available, is lost opportunity waste and should be avoided.

**Table 1.** Key material properties for some of common tool steels used for manufacturing extrusion tooling.

| Material | Strength at 932°F/500°C (ksi/MPa) | Annealing Temperature (°F/°C) | Toughness | Thermal Conductivity (W/mK) RT-930°F/500°C | Cost Factor | Hardness (HRC) |
|---|---|---|---|---|---|---|
| **ConDuct** | **116**/800 | **1022**/550 | 100J | 45-42 | 150 | 34-36 |
| **L6 (1.2714)** | **145**/1000 | **1058**/570 | 40J | 36-35 | 250 | 38-42 |
| **H11** | **145**/1000 | **1085**/585 | 30J | 25-30 | 200 | 38-42 |
| **H13** | **160**/1100 | **1085**/585 | 25J | 24-29 | 200 | 38-48 |
| **E40K**<br>**Q10**<br>**DAC3**<br>**1.2367** | **160**/1100<br>**174**/1200<br>**189**/1300<br>**189**/1300 | **1103**/595 | 35J | 30-35 | 400 | 44-52 |

Figure 1 shows simulation predictions for a three-piece container under steady state working conditions. Two different materials have been assigned to sub-liner and results compared to each other. H13, a super hard steel with low thermal conductivity (Figure 1, left) and ConDuct, a high-strength steel (lower strength compared to H13) with much higher thermal conductivity. Based on simulation results for both cases, the sub-liner is under less stress both effective stress (von Mises) and hydrostatic, than liner and mantle. On the other hand, due to better thermal conductivity of the Conduct sub-liner, there is less thermal stress produced between the parts. In addition, the Conduct sub-liner can dissipate more heat to the outside so that the container gets more resistant to thermal saturation. Another factor that makes this material selection more pleasant is less material cost for ConDuct than for H13.

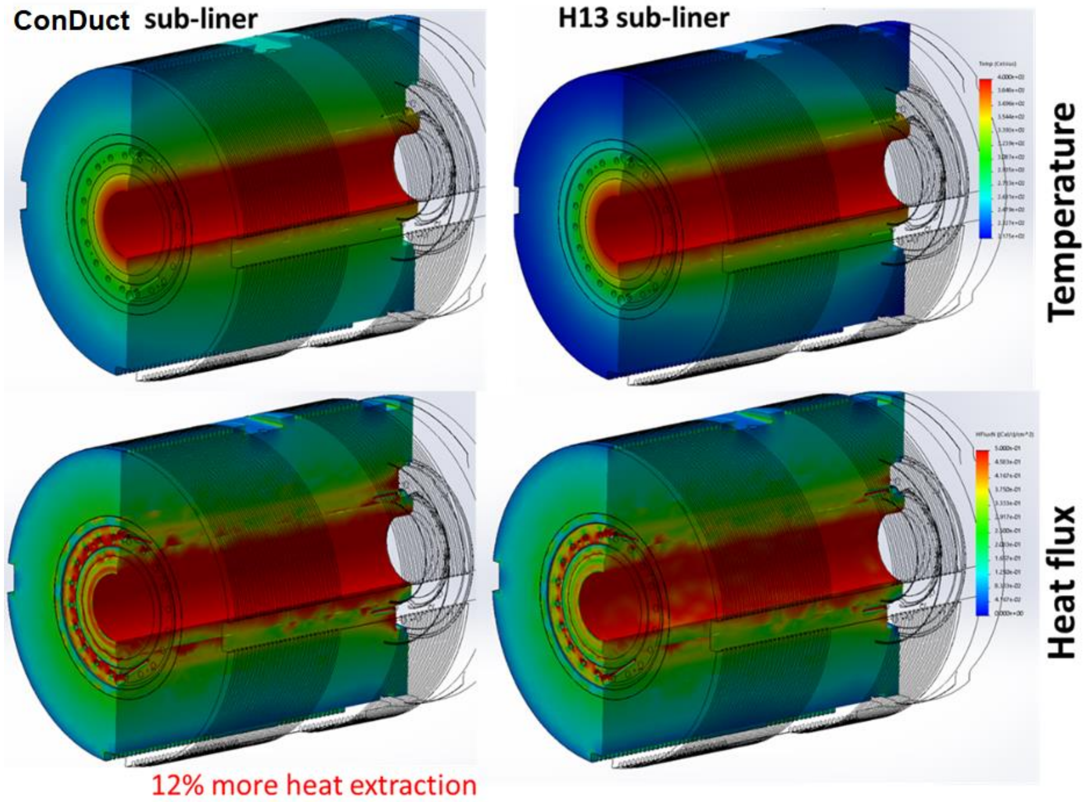


**Figure 2.** Temperature and heat flux in container with ConDuct sub-liner (left); vs. H13 sub-liner (right).

## Alloy Effect

From a metallurgical point of view, adding alloying elements decreases the melting point of aluminum drastically, but at the same time, higher temperature is needed to bring the alloying elements back to solution, which is important during the extrusion of heat-treatable alloys such as 6xxx-series and 7xxx-series alloys. The temperature at which the melting starts is called “solidus” and the minimum temperature needed to bring alloying elements into solution is called “solvus.” During extrusion, we need the exit temperature to be anything between solvus and solidus to have both good surface quality and desired microstructure at the same time. It is important to remember that the solvus is the temperature that puts Mg and Si into solid solution when there are large amounts of time available. To achieve T4 or T6 tempers, there has been a requirement that the temperature of the alloy must be high enough at press exit to fully solutionize the Mg and Si in the time available. [16] That time is not long, as it represents the distance between the die exit and the quench system divided by the exit speed. To achieve full solutionizing of the Mg and Si in that time (often in the range of 5 to 10 seconds) demands a temperature well in excess of the solvus.

Referring to the following table, the solvus-solidus window can change from 170°F (95°C) for AA6063 down to 13°F (7°C) for AA6082. A narrow temperature control window makes this more difficult to control the exit temperature. Generally, harder alloys with more alloying elements have a smaller temperature control window. However, the harder alloys have a more demanding specification for the end product. Thus, while the window of operating temperature is smaller, the consequences of failing to stay within the window are much more significant.

**Table 2.** Extruded aluminum alloys: specifications and extrusion process conditions.[17, 18, 19]

| Alloy | | Chemical Composition | | | | | | | Favorable exit temperature (Solvus - Solidus) | | Temperature control window | | Exit speed [ft/min] | Cycle time [minutes] ER=50 40" long billet | Face pressure [ksi] | Heat generation in container [kW] | Heat Dissipation required [kW] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Si | Mg | Mn | Cr | Cu | Zn | Zr | °C | °F | °C | °F | | | | | |
| Soft | 1100 | | | | | 0.1 | | | < 643 | < 1190 | | | 164-262 | 1-2 | 60 | 45 | 25 |
| | 3003 | | | 1.2 | | 0.1 | | | < 643 | < 1190 | | | 98-230 | 1-2 | 70 | 53 | 27 |
| | 6063 | 0.4 | 0.7 | | | | | | 520 - 615 | 970 - 1140 | 95 | 170 | 115-262 | 1-2 | 80 | 60 | 30 |
| Medium | 6005A | 0.8 | 0.5 | 0.15 - 0.5 | | | | | 530 - 600 | 985 - 1110 | 70 | 125 | | | 90 | 23 | 15 |
| | 6061 | 0.6 | 1 | | 0.2 | 0.3 | | | 560 - 582 | 1040 - 1080 | 22 | 40 | 16-82 | 3-10 | 90 | 23 | 15 |
| | 6082 | 1 | 1 | 0.6 | 0.3 | | | | 570 - 577 | 1058 - 1071 | 7 | 13 | | | 90 | 23 | 15 |
| | 7003 | | 0.7 | | | | 6 | 0.8 | 540 - 600 | 1000 -1110 | 60 | 110 | 16-69 | 4-10 | 90 | 23 | 15 |
| Hard | 7075 | | 2.5 | | 0.2 | 1.6 | 6 | | 465 - 480 | 870 - 895 | 15 | 25 | 3-7 | 25-55 | 100 | 3 | 3 |

Aluminum alloys are among the most extrudable metals, due to minor flow stress at high temperature. The hot flow stress of aluminum can be increased by a level of magnitude just by adding a few percent of alloying elements. Under the same temperature and deformation rate, AA7075 is 10 times stronger than commercially pure aluminum (AA1050). This huge difference in flow stress will translate into a large range of extrudability, where a soft aluminum alloy can be extruded about two levels of magnitude (100 times) faster than a hard aluminum alloy. Slower ram speed during extrusion results in less heat generation from billet deformation inside the container, such that during the extrusion of AA7075, the cycle time is too long, so that the rate of heat dissipation through the container is much more than the heat generation rate inside the container, which is opposite the situation during the extrusion of soft alloys where heat generation in the container wins the heat dissipation of the container, and the container becomes thermally saturated. The power of heat dissipation in the container is a function of thermal conductivity, design, and the outside cooling method. Based on the aluminum alloy to be extruded, a proper combination of these parameters must be chosen to provide required heat dissipation power.

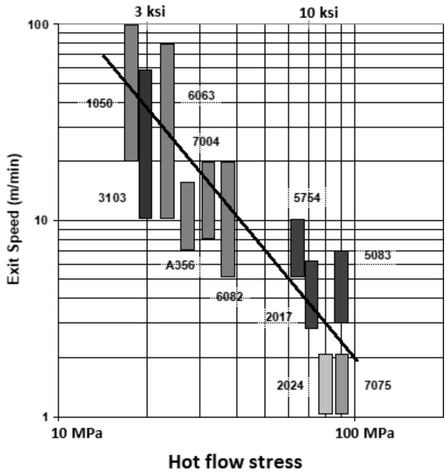


**Figure 3.** Extrusion exit speed vs. low stress of selected aluminum alloys.[20]

In addition to more temperature sensitivity, harder alloys need more extrusion load (often requiring significantly higher specific pressure presses), so that there is more load applied on the tooling including container and dummy block, and in that case, using stronger material may be necessary. The image below shows the stress distribution during the extrusion of a hard alloy with high pressure of 117ksi (807MPa) where the stress transferred to the sub-liner is close to yield stress of the ConDuct material. Under the same thermal conditions, the container with an H13 sub-liner exhibits better support on the liner, so that the liner is under less deformation. At the same time, the stress level on the sub-liner remains the same as the ConDuct sub-liner. The lower conductivity of H13, compared to ConDuct conducts away less heat through the container, and that represents a challenge in these high-strength alloys where the solvus solidus temperature range is small.

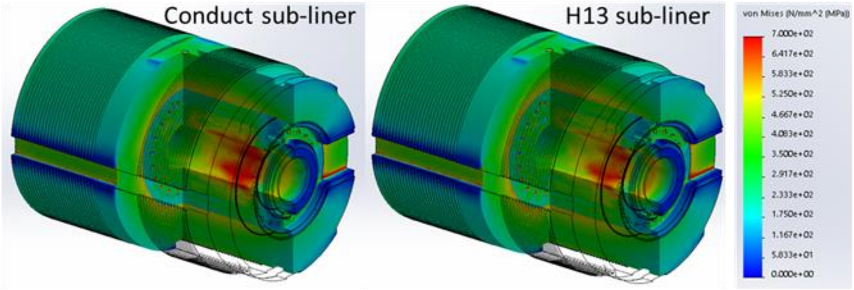


**Figure 4.** Stress distribution during the extrusion at peak face pressure of 117ksi (807MPa) in a three-piece container with an H13 liner and ConDuct body, and different sub-liner material.

## The Die Design

Die design can play a big role in the extrusion process as a large part of the deformation and hence, temperature rise is taking place inside the die. Everything happens so fast [21] inside the die; the deformation heat usually does not have enough time to dissipate, and it remains in the material and adds up to exit temperature. As a result, optimization of the die design to produce less heat can play a better role here, rather than heat dissipation techniques.

A simulation-based study has been performed using FE-based software HyperExtrude® to observe the effect of die design on exit temperature and productivity improvement. Three different die sets, nominally die 1, die 2, and die 3, were designed and modeled with different portholes and chamber sizes in Figure 5. All the die sets have the same die plate and mandrel core shape, so that they are producing the same profile geometry. The size of portholes and welding chambers increases from die 1 to die 3, making die 1 the easiest and die 3 the hardest one to push. Die 2 seats somewhere in between where it has wider porthole openings than die 1 but has the same size of welding chambers as die 1.

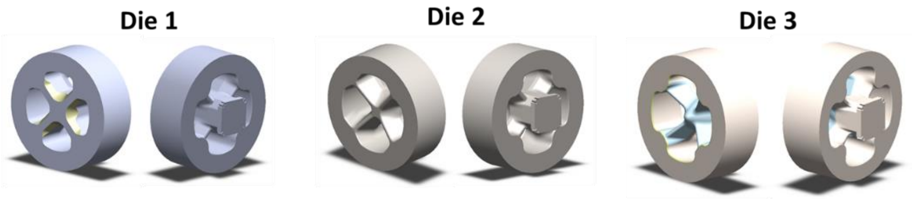


**Figure 5.** The three die designs used in the study.

Model predictions show that extrusion load and exit temperature can reduce significantly by just widening the pockets in the die set. This helps the extruder to be able to speed up the press to improve productivity.

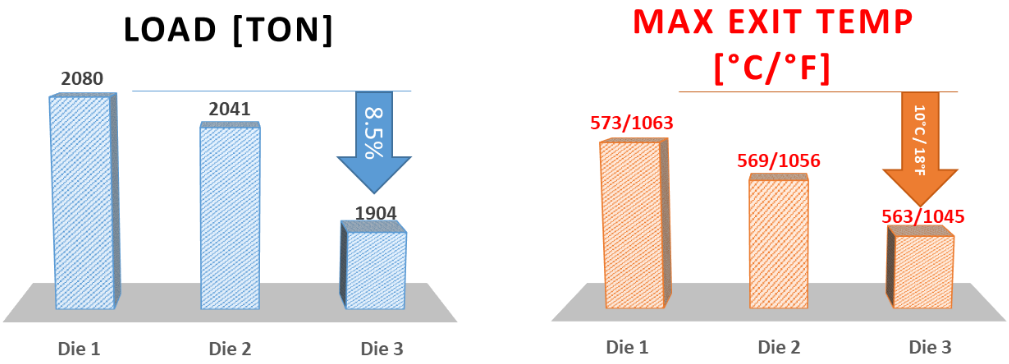


**Figure 6.** Model predictions for extrusion loads and maximum temperature across the profile at die exit.

The first two rows in Table 3 show the predicted exit temperature and load for die 1 and die 3, with the same ram speed (24in/min), and the third row is showing the model predictions for die 3, with a 30 percent higher ram speed (31in/min) to match the exit temperature of die 1 (first row). It is interesting that with increasing the ram speed by 30 percent on die 3, the extrusion load is just increased by 25 percent of the difference between die 1 and die 3, but the temperature difference is fully compensated. This means that the exit temperature is much more sensitive to ram speed than the extrusion load (four times more sensitive in this case).

**Table 3.** 30 percent ram speed improvement with die 3.

| | Ram Speed [in/min] | Max. Exit Temp. [°F] | Load [ton] |
|---|---|---|---|
| **Die 1** | 24 | 1063 | 2080 |
| **Die 3** | 24 | 1045 | 1904 |
| **Die 3** | 31 | 1063 | 1926 |

One may ask: what about front scrap increase as a result of bigger ports in the die? Table 4 shows required data to understand how big the effect of die modification on recovery is. As an over-estimation, if one assumes that the material from previous billet trapped in the die set is scrapped, the percentages of front scrap for die 1, die 2 and die 3 are 3.9 percent, 4.4 percent, and 5.3 percent, respectively. This means that moving from die 1 to die 2, the front scrap will increase at most by 0.5 percent. The front scrap increase is at most 1.4 percent when die 1 is replaced by die 3.

This drop of recovery is considered for productivity calculations in the following sections of the paper. It will be observed that when using die 2 and die 3, the minor drop in recovery is ignorable, compared to the big increase in productivity.

**Table 4.** Effect of die design on total volume of ports and estimation of front scrap.

| | Volume of ports ($in^3$) | Equivalent length of 9-inch diameter billet (inch) | Fraction of 36-inch-long billet (%) |
|---|---|---|---|
| **Die 1** | 90 | 1.4 | 3.9 |
| **Die 2** | 99 | 1.6 | 4.4 |
| **Die 3** | 121 | 1.9 | 5.3 |

## Optimization of the Extrusion by Balancing Multiple Process Parameters

In this study, seven parameters (or factors) listed in Table 5, were chosen for optimization. A combination of tooling parameters (i.e., container size and die design), and adjustable process conditions (i.e., ram speed, billet preheat temperature and billet length) were taken into account. Two extra parameters are considered related to heat dissipation capacity of the container (i.e., container conductivity and outside cooling). These two parameters are not usually considered by both extruders and press manufacturers. The material of choice for this study is the most popular extruded aluminum alloy AA6063, which is categorized as a soft 6xxx-series aluminum alloy. The results and conclusions of this study can be imposed onto other materials qualitatively.

**Table 5.** 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) | 5 (Air) | 10 (Forced Air) | 15 (Comp. Air) |
| 3 | **RS** | Ram Speed (mm/s) | 3 (7 in/min) | 5 (12 in/min) | 7 (17 in/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) |

Based on the number of factors and levels, Taguchi's L18 orthogonal design of experiments [22] is used to analyze the effect of these parameters on extrusion loads and temperatures and finding the best combination to improve productivity. There are 18 finite element (FE) simulations performed with different combinations of parameter values, and results are extracted for loads and temperatures, as observed in Table 6. Bennett numbers and net productivity are also calculated for each case, based on regular extrusion practices.

**Table 6.** Taguchi L18 design of experiments and model predicted responses for extrusion load and maximum exit temperature.

| # | Parameters | | | | | | | Model predictions | | Bennett Numbers | | | Net Productivity (lb/hr) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | CC | OC | RS | BT | BL | BD | DD | Load (ton) | Exit Temp. (°C) | Contact Efficiency % | Recovery % | Ram Speed* in/min | |
| **1** | 24 | 2 | 7 | 790 | 28 | 7 | 1 | **1960** | **534** | 79 | 80 | 5.4 | **1111** |
| **2** | 24 | 2 | 12 | 840 | 32 | 8 | 2 | **2285** | **568** | 72 | 83 | 12.0 | **2319** |
| **3** | 24 | 2 | 17 | 900 | 36 | 9 | 3 | **2678** | **597** | 67 | 85 | 21.3 | **3937** |
| **4** | 24 | 5 | 7 | 790 | 32 | 8 | 3 | **2384** | **532** | 82 | 83 | 7.0 | **1521** |
| **5** | 24 | 5 | 12 | 840 | 36 | 9 | 1 | **3037** | **576** | 74 | 86 | 15.0 | **3111** |
| **6** | 24 | 5 | 17 | 900 | 28 | 7 | 2 | **1715** | **578** | 61 | 80 | 13.2 | **2072** |
| **7** | 24 | 8 | 7 | 840 | 28 | 9 | 2 | **2624** | **545** | 79 | 84 | 8.8 | **1886** |
| **8** | 24 | 8 | 12 | 900 | 32 | 7 | 3 | **1606** | **557** | 72 | 80 | 9.3 | **1735** |
| **9** | 24 | 8 | 17 | 790 | 36 | 8 | 1 | **2799** | **571** | 67 | 85 | 17.0 | **3116** |
| **10** | 42 | 2 | 7 | 900 | 36 | 8 | 2 | **2027** | **559** | 83 | 84 | 7.0 | **1579** |
| **11** | 42 | 2 | 12 | 790 | 28 | 9 | 3 | **2992** | **548** | 69 | 84 | 15.0 | **2802** |
| **12** | 42 | 2 | 17 | 840 | 32 | 7 | 1 | **1980** | **577** | 65 | 81 | 13.2 | **2229** |
| **13** | 42 | 5 | 7 | 840 | 36 | 7 | 3 | **1768** | **533** | 83 | 81 | 5.4 | **1184** |
| **14** | 42 | 5 | 12 | 900 | 28 | 8 | 1 | **2068** | **574** | 69 | 83 | 12.0 | **2211** |
| **15** | 42 | 5 | 17 | 790 | 32 | 9 | 2 | **3248** | **571** | 65 | 85 | 21.3 | **3767** |
| **16** | 42 | 8 | 7 | 900 | 32 | 9 | 1 | **2505** | **570** | 82 | 86 | 8.8 | **1971** |
| **17** | 42 | 8 | 12 | 790 | 36 | 7 | 2 | **2277** | **522** | 74 | 82 | 9.3 | **1825** |
| **18** | 42 | 8 | 17 | 840 | 28 | 8 | 3 | **2241** | **565** | 61 | 82 | 17.0 | **2743** |

* Ram speed equivalent to 8-inch container.

## Analysis and Optimization

Main effects of different process parameters are shown in plots presented in Figure 7. Looking into these plots gives an idea about the significance of each parameter and how it affects the responses of interest (in this case load and exit temperature).

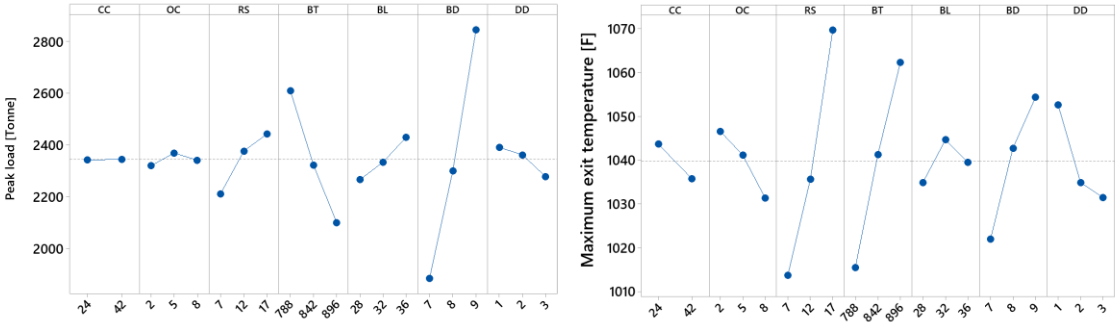


**Figure 7.** Main effects of extrusion process parameters on extrusion load and exit temperature.

Using regression and curve fitting techniques the maximum possible profile speed is estimated for each of 18 cases (Table 7). Process limits used are as follows:

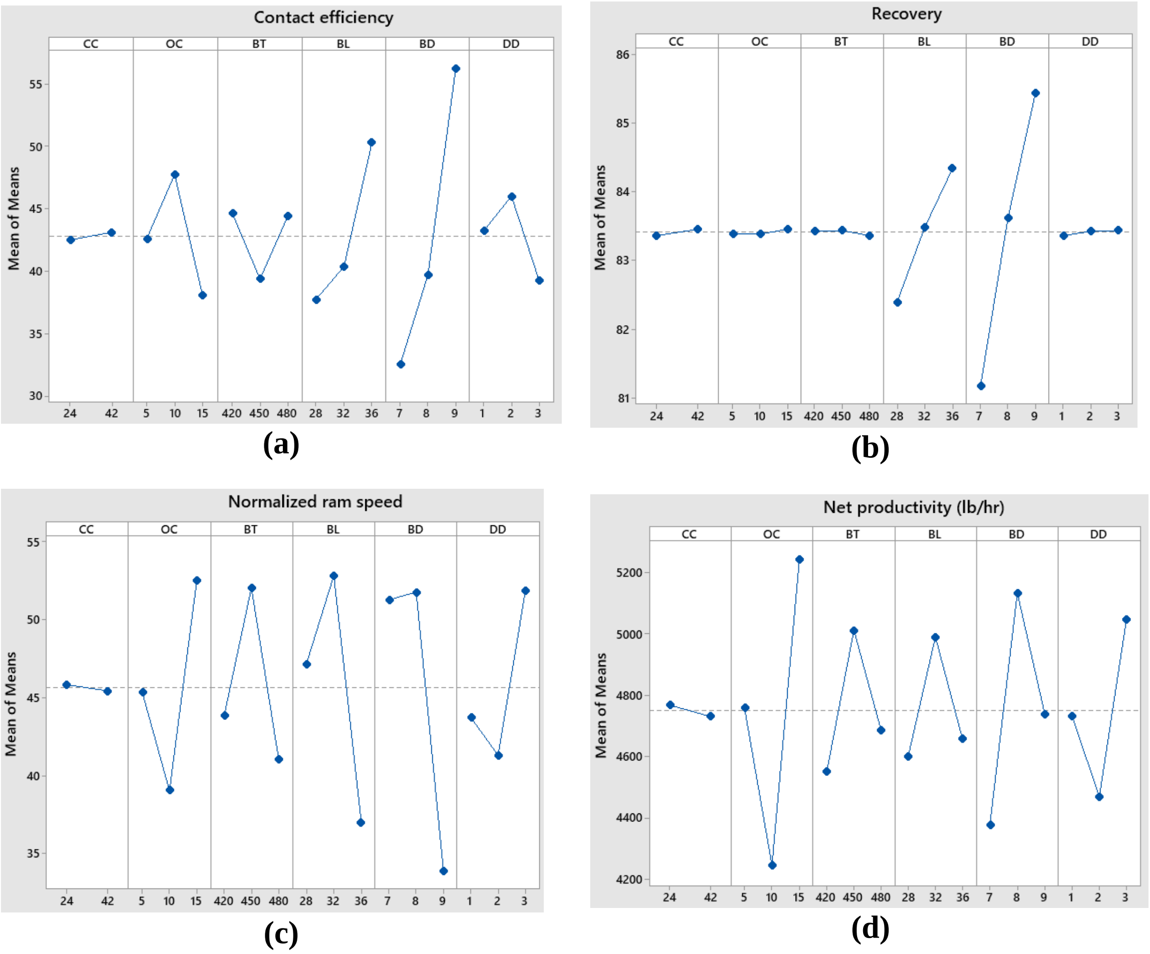
1- Maximum exit temperature must be below 1110°F (600°C)
2- Extrusion load cannot exceed 2750 tons (press capacity)
3- Profile speed must be below 100m/min (puller speed capacity)
4- Ram speed cannot exceed 70in/min (press speed capacity).

**Table 7.** Maximum possible extrusion speed and productivity.

| # | Parameters | | | | | | Responses for maximum extrusion speed | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | CC | OC | BT | BL | BD | DD | Maximum Profile Speed (m/min) | Bennett Numbers: Contact Efficiency (%) | Bennett Numbers: Recovery (%) | Bennett Numbers: Eq. Ram Speed* (in/min) | Net Productivity (lb/hr) |
| **1** | 24 | 2 | 790 | 28 | 7 | 1 | **55** | 36 | 80 | 38 | **3479** |
| **2** | 24 | 2 | 840 | 32 | 8 | 2 | **42** | 51 | 84 | 29 | **4067** |
| **3** | 24 | 2 | 900 | 36 | 9 | 3 | **32** | 67 | 86 | 22 | **4080** |
| **4** | 24 | 5 | 790 | 32 | 8 | 3 | **36** | 56 | 84 | 25 | **3711** |
| **5** | 24 | 5 | 840 | 36 | 9 | 1 | **9** | 87 | 86 | 6 | **1538** |
| **6** | 24 | 5 | 900 | 28 | 7 | 2 | **34** | 47 | 80 | 24 | **2871** |
| **7** | 24 | 8 | 840 | 28 | 9 | 2 | **20** | 71 | 85 | 14 | **2694** |
| **8** | 24 | 8 | 900 | 32 | 7 | 3 | **44** | 44 | 81 | 31 | **3540** |
| **9** | 24 | 8 | 790 | 36 | 8 | 1 | **16** | 75 | 85 | 11 | **2339** |
| **10** | 42 | 2 | 900 | 36 | 8 | 2 | **32** | 61 | 85 | 22 | **3675** |
| **11** | 42 | 2 | 790 | 28 | 9 | 3 | **10** | 83 | 85 | 7 | **1605** |
| **12** | 42 | 2 | 840 | 32 | 7 | 1 | **41** | 46 | 81 | 28 | **3408** |
| **13** | 42 | 5 | 840 | 36 | 7 | 3 | **63** | 38 | 82 | 44 | **4442** |
| **14** | 42 | 5 | 900 | 28 | 8 | 1 | **32** | 54 | 83 | 23 | **3271** |
| **15** | 42 | 5 | 790 | 32 | 9 | 2 | **6** | 91 | 86 | 4 | **1013** |
| **16** | 42 | 8 | 900 | 32 | 9 | 1 | **31** | 64 | 86 | 21 | **3811** |
| **17** | 42 | 8 | 790 | 36 | 7 | 2 | **78** | 33 | 82 | 54 | **4794** |
| **18** | 42 | 8 | 840 | 28 | 8 | 3 | **76** | 34 | 83 | 53 | **4761** |

* Ram speed equivalent to 8-inch container.

Now let’s look at the main effects of process parameters on Bennett numbers and net productivity for maximum possible extrusion speed. As observed in Figure 8, except for recovery, process parameters do not show a consistent and meaningful effect of Bennet numbers and net productivity for maximum speed. Only recovery shows a meaningful trend, as it is only a function of billet dimensions, and ram speed does not affect it at all. It may not be possible to define a simple relation between given process parameters and optimum productivity.



(a) (b)

(c) (d)

**Figure 8.** Main effect of process parameters on Bennet numbers and productivity for the maximum extrusion speed: a) contact efficiency; b) recovery; c) ram speed; and d) net productivity.

To find the optimum productivity, maximum extrusion speed was calculated for the full range of six parameters listed in Table 7 (all seven parameters except ram speed) with five levels for each parameter to get better accuracy. Then productivity and Bennett numbers were calculated for each case. Table 8 shows the parameter recipes that result in maximum and minimum (extremum) productivities. There are two sets of extremums: global extremums and mediocrity extremums. Global extremum is with considering all possible combinations of parameter values, while mediocrity is for cases where the extruder uses a regular low conductive container, poor container cooling, and a hard to push die.

The best global recipe with a net productivity of 5428lb/hr represents the excellent process conditions where the heat dissipation is highest and an easy to push die is used. In this case, the extrusion exit temperature is at the maximum allowed point (1110°F) and the press is running close to maximum capacity. It is interesting that the global minimum productivity (610lb/hr) is also with high thermal dissipation where the extruder uses a cold billet so that the press load capacity becomes the limit. On the other hand, if mediocre conditions are followed where the container does not have a good heat dissipation capacity and the die is a conservative hard to push die, then the net productivity cannot exceed 4147lb/hr.

This means that applying better heat dissipation and die design can improve productivity by 30 percent. One must keep in mind that these numbers are for the case that all other parameters are optimized.

**Table 8.** Predicted process parameters for extremum (max/min) productivity (global extremum is with considering all possible combinations of parameter values, while mediocrity is for cases where the extruder uses regular low conductive container, poor container cooling and hard to push die).

| Variable | Global extremums | | Mediocrity extremums | |
|---|---|---|---|---|
| | Best recipe | Worst recipe | Best recipe | Worst recipe |
| **Container conductivity** | 42 | 42 | 24* | 24* |
| **Outside cooling** | 8 | 8 | 2* | 2* |
| **Billet temperature (°F)** | 815 | 788 | 788 | 788 |
| **Billet length (in)** | 36 | 36 | 32 | 36 |
| **Billet diameter (in)** | 7.5 | 9 | 7.5 | 9 |
| **Die design** | 3 | 1 | 1* | 1* |
| **Max. achievable Profile speed (m/min)** | 86 | 3 | 53 | 4 |
| **Extrusion load at max. (ton)** | 2750 | 2750 | 2750 | 2750 |
| **Exit temperature at max.(°F)** | 1110 | 923 | 1110 | 950 |
| **Contact efficiency** | 34 | 95 | 43 | 95 |
| **Recovery** | 82 | 86 | 83 | 86 |
| **Ram speed (in/min) (Equivalent to 8" billet)** | 68 | 1.8 | 37 | 2 |
| **Net Productivity (lb/hr)** | 5428 | 610 | 4147 | 664 |

* Kept constant to represent classic extrusion conditions.

It is worthwhile to mention that using mediocre extrusion conditions, the worst-case scenario is better than the global minimum (664lb/hr vs. 610lb/hr). This means that the extruders that are looking for excellence and higher productivity by increasing the heat dissipation and improving die design must be more careful with tuning other process parameters such as billet temperature and ram speed; otherwise, they may fall behind a conservative extruder.

As mentioned earlier, the effect of front scrap increase as a result of bigger die ports is considered for productivity optimization calculations. Based on data provided in Table 9, the productivity increases by 8 percent and 16 percent when using die 2 and die 3 instead of die 1, while the recovery only drops by 0.5 percent and 1.5 percent.

**Table 9.** Model predicted productivity and recovery.

| | Optimum productivity (lb/hr) | Normalized productivity | Recovery (%) |
|---|---|---|---|
| **Die 1** | 4690 | 100 | 83 |
| **Die 2** | 5088 | 108 | 82.5 |
| **Die 3** | 5428 | 116 | 81.5 |

All the optimizations so far have been done based on press load capacity of 2750 tons. What if the press capacity is lower or higher? Table 10 shows the predicted optimum recipe for different press load capacities. It is observed that for all cases, the optimum recipe includes highest conductivity and outside cooling. Optimum billet temperature decreases with press capacity while optimum billet diameter increases.

**Table 10.** Predicted process parameters for maximum productivity with different press capacities.

| Variable | Press load capacity (ton) | | | |
|---|---|---|---|---|
| | **2500** | **2750** | **3000** | **3250** |
| **Container conductivity** | 42 | 42 | 42 | 42 |
| **Outside cooling** | 6.5 | 8 | 8 | 8 |
| **Billet temperature (°F)** | 850 | 820 | 810 | 800 |
| **Billet length (in)** | 34 | 36 | 36 | 36 |
| **Billet diameter (in)** | 7.5 | 7.5 | 8 | 8.5 |
| **Die design** | 3 | 3 | 3 | 3 |
| **Max. Net Productivity (lb/hr)** | 4719 | 5428 | 5933 | 6400 |

## SUMMARY AND CONCLUSIONS

Every year the market for extrusion becomes more demanding. Extruders are required to produce profiles with thinner walls, more features, stronger mechanical strength and better finishes, all while using alloys that vary in extrudability and other properties. Those extruding 6063 simple profiles are now few and far between.

Fortunately, one now better understands the distribution of heat in the extrusion process and in a key element within the process, the container. This understanding goes beyond the simple understanding in terms of strength. It includes the thermal balances in the process, and the effects of this balance on the die and profile temperature, which in turn impacts the metal flow. Any part of the process that increases temperature potentially reduces ram speed! Any part of the process that increases resistance to flow has a doubled effect: the resistance to flow uses up press force while generating redundant heat. Both of these are unfavorable to high productivity. Any part of the process that causes temperature instability requires a die with more features that use friction to gain control of flow, which again reduces ram speed. Super-extruders obviously didn't get to be Super-extruders purely by luck, and it's unlikely that they have all shared the same magic formula for success, but there are things they have in common. When one looks at their net productivity gain over the average, numbers are seen in the 40 to 50-percent range. What average extruder wouldn't want to see that kind of improvement?

The most important concept to take away from this discussion of the three factors of material, time, and speed is balance. If one attempts to push the envelope on any of them individually, one runs the risk of failure in the others, and productivity (and of course profit) goes out the window. Understanding this balance is the first prerequisite to becoming a Super-extruder. The path to getting there may vary. It depends on all of the physical factors of a given extruder's equipment, their operators, how diligent they are in following procedures, how carefully they measure and control temperatures, and ultimately how much they care about producing a final product that maximizes quality and profitability.

The information is out there. The average extruder can learn, implement new procedures and techniques, become more diligent, and in short, can become Super!

It must be kept in mind that becoming a Super-extruder needs balancing and fine tuning all of the important process parameters together. Focusing on one or a few parameters and forgetting others may give an opposite result, and cause productivity to drop below mediocrity.

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