The Design and Benefits of a Thermally Stable Container

Paul Robbins[1], Ken Chien[1], Chris Jowett[2] and Bill Dixon[3]
[1] Castool Tooling Systems, Uxbridge, Canada
[2] Rio Tinto, Kingston, Canada
[3] QED Extrusion Developments, Escondido, USA

ABSTRACT:

The paper addresses how the thermal and mechanical design of a container influences liner bore and container body temperatures, operating stress levels, billet skin inflow, and tooling life. To help better understand container performance; modeling is presented for various container designs and heating concepts. Based on the data, the paper describes how heating elements and thermocouple configurations along with best design and operating practices can achieve thermal stabilization. This contributes to both improved mechanical and thermal container performance, leading to extended container life and reduced process scrap.

By process of improved and controlled billet flow into the die, resulting from container thermal stability, extrusion surface defect issues and run out variations are reduced, as well as improved extrusion dimensional consistency. This drives optimization and increased productivity.

INTRODUCTION:

As was said in their book "Extrusion" [1], K. Laue and H. Stenger "The efficiency of the extrusion process depends to a very high degree on the durability of the container, with the life of the inner liner being the most important". This might have been the consideration in 1981, but is probably a minimum requirement today; a far more important property from the point of view of extrusion productivity and quality is that the heating system is more responsive and controls the temperature of the liner by the minute rather than by the hour.

The key requirement of the container and it's heating system is that it controls the temperature of the liner within each of up to 8 zones and that it does so rapidly. For example, when the press is being used 5 days a week or 16 out of 24 hours per day, it is impossible for external heaters to give the necessary response. For that reason, the authors argue that the only practical control system is to have multi-zone control with heaters and thermocouple located as near the liner as possible. In addition, the use of cooling channels near the liner is then unnecessary and removal of heat from the liner by conduction to a relatively cool container is preferred.

CONTAINER DESIGN EVOLUTION:

Mechanical Strength and the ability to withstand pressure at temperature.

The container is one of the most expensive consumable components in the press. It is naturally important that it lasts a long time and requires infrequent re-lines. It is also a component that has a significant influence on the "availability" of the press to produce extrusions of high quality. The container and liner assembly are under extreme cyclical loading which produce elastic deformation of the inner liner, thus being critical to the functioning of the dummy block. Both the liner bore inside diameter and the fixed dummy block expanded diameter vary significantly during the extrusion of the billet due to pressure and temperature changes. This includes both the hydrostatic pressure within the extrusion billet and the axial

loading resulting from the shear between billet and liner surface. These pressure and loading components vary from a maximum just after break-through to close to zero at the end of the extrusion stroke.

In most cases containers are constructed from two or three components each shrunk fit to reduce tensile stresses. Calculation of the stresses is relatively simple using thick cylinder theory as described by Laue and Stenger and others [2, 3]. Laue and Stenger explain in more detail how thick cylinder theory is used to calculate the stresses in the multi-piece container assemblies. A simple 2-piece container (body + liner) with 2 temperature control zones at the rear and the die end is shown in Figure 1. This type of container is suitable for smaller presses of 7" or less, and extrusion of 6xxx series alloy.
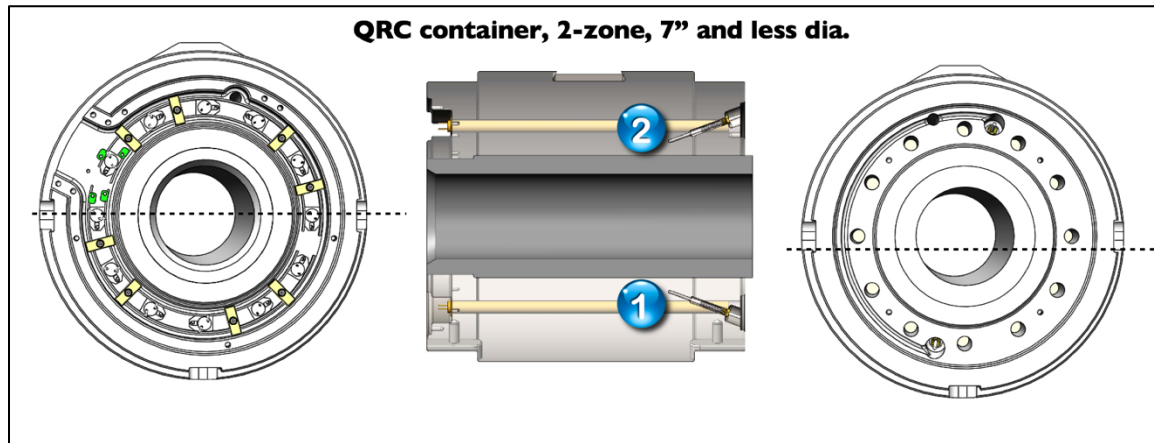

Figure 1: A 2-piece, 2 zone QR container.

The influence of temperature in determining the stress in the container cannot be ignored, both during preheating and during production. Thermal expansion effects can be very large due to differences in temperature throughout the assembly as well as a reduction in the strength of the tool steel. Strehl et al [4] reported how the stresses from the shrink fitting of containers and liners interact with stresses caused by temperature gradients within the assembly.

The container heating system and thermocouple location.

The objective of the heating system in a conventional container was well documented in 2004 by Van Dine et al of Castool [5]. Here the objective was to try and control the container temperature such that it is relatively uniform, with perhaps a requirement of extra heating at the bottom to compensate for heat loss to the press frame. Eckenbach et al [6, 7] introduced a sophisticated temperature control system for preheating and extruding that controlled multi-zone heaters, and introduced the phrase "Smart Containers".

As discussed in their paper in Light Metal Age [8], Robbins and Chien suggest the goal of container heating is to have temperature stability of the liner, not temperature uniformity of the mantle - indeed temperature uniformity may not be beneficial as it discourages heat flux and cooling, both radial and longitudinal. Clearly, the container and press tooling need to be heated to allow extrusion of a hot billet, yet once extrusion has started the accumulation of excess heat from deformation of the billet becomes a liability and must be removed. Most of the heat of deformation is generated primarily in the zone directly in front of the die and also at the liner surface. An average temperature rise of the order of 150°C can be achieved. This heat generation is extremely non-uniform and much of the heat goes into the die and from there out with the extrusion. Yet a significant portion transfers into the container liner and then into the main body of the container. With controlled heat flux and transfer in the container body, heat can no longer accumulate and thermal consistency is maintained. The container then has the desired thermal stability characteristics.

The balance between maintaining the tooling at a minimum temperature prior to extrusion and then minimizing the temperature rise during extrusion is a challenge for the temperature control system. It is immediately clear why one needs to be able to control the liner temperature by the minute rather than by

the hour. And this can only be done with a local heat source close to the billet. In other words, this can only be achieved with quick response cartridge heaters very close to the liner and control thermocouples also placed as near as possible to the liner bore. Combined with this, heat has to be extracted when the control temperature is exceeded requiring high conductivity from the hot zone to the container. Radial conduction can be high with a thin hot liner and a large relatively cool container made with high conductivity steel such as SAE 4340.The use of cooling channels cannot be ruled out, but it is the authors contention that this is best done at the outside of the container mantle, and reserved for special cases involving very high productivity extrusion.

The best heating system is therefore one that independently controls all parts of the liner, both top and bottom at the "die end" to compensate for heat losses into the cooler press frame and with axial taper to assist heat removal from the deformation zone. The basis of the approach is to eliminate temperature fluctuations caused by the heating elements being placed too far from the liner, or by cooling channels adjacent to the liner. Such a container is an advancement on that shown in Figure 1, and takes the basic design to a range of "thermally stable" designs that cater for a wide range of applications from soft to hard alloy extrusion, on presses up to large container diameter, both round container and rectangular, and for longer container lengths at high specific pressure.

Later data is presented indicating liner bore temperature and die bearing temperature during extrusion of a sequence of billets. The data show that temperature at the die is very much dependent on the liner surface temperature. Any temperature drifting because of lack of thermal control within the container will cause the die temperature to fluctuate, resulting in problems of surface finish, run-out length and shape.

Temperature instability influences alignment and causes liner bore diameter variations, and more importantly variation between the axis of the liner in relation to the axis of the press. Clearly this variable thermal misalignment can be critical to die performance and extrusion quality.

As the objective is to establish thermal stability in a container and thereby enjoy improved process consistency, what are the obstacles in doing so? Is there a "Monday morning effect" following start-up after a weekend delay, and how long does it take the container to reach stability after start-up, and to what extent may extrusion productivity and quality be influenced during this start-up interval? How long does it take for a container to recover to the desired set point temperatures, after cooling to a lower stable temperature over a lengthy downtime period such as a weekend stoppage. Figure 2 indicates the loss of thermal stability than can arise following an extended shutdown such as a weekend scheduled stoppage, comparing a container heated with external elements (Figure 2a), with elements placed sub-optimally in the container body i.e. at mid radius (Figure 2b), or with elements optimally located close to the liner (Figure 2c).
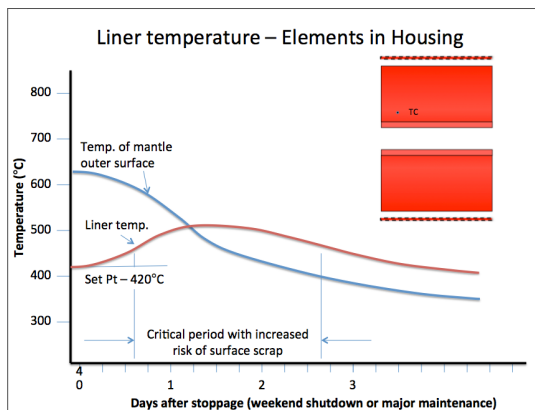
(a)
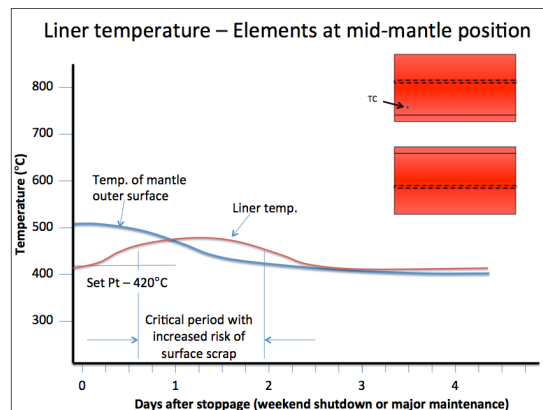
(b)
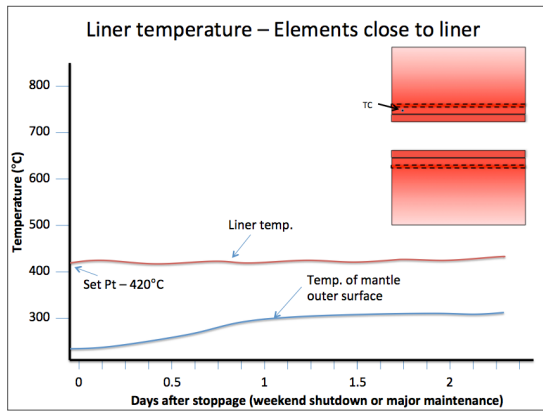
(c)

Figure 2: Effect of element location in a container, and the loss of thermal stability after an extended stoppage when elements are external (a), or placed at centre container thickness (b), compared with no loss in stability when place close to the the liner (c).

The images in Figure 2 portray a clear picture, and raise questions relating to temperature stability in the container, and its effect on thermal stability of the extrusion process as a whole. Elements located in sub-optimal locations will result in a period where the container liner is at risk of overheating as the elements strive to recover the residual heat lost during the stoppage. In both cases (a) and (b), and worse so in case (a), the elements are displaced from the control thermocouples further than in case (c), having slower response and taking longer to stabilize to the desired set point temperatures. Zones with lower set points such as rear zones operating with a longitudinal offset where the rear zones are set colder than those at the die, will encounter less of a problem. However, the situation can become critical in the die end zones, where a period when the liner is allowed to overheat, will result in increased extrusion surface defects, dimensional issues and overall reduced productivity.

One thing is sure, few extruders will waste energy by leaving a container running at set point(s) in the event of an extended stoppage whether scheduled or not, yet no-one should consider completely switching the container off for a delay of no more than a few days due to thermal stress risks associated with complete cooling and reheating. The best practice in the event of a relatively short delay is to set each zone to a lower temperature of around 350°C (662°F). To minimize convective losses from the interior of the container liner to the surrounding atmosphere, the stem and dummy block should be inserted approximately 50-75% and the container closed onto a die set in the die cassette, but not necessarily held with container sealing pressure.

The use of well designed containers able to minimize the loss in thermal stability, by smarter location of elements, goes a long way to eliminating the potential problems.

The above is one challenge encountered with container heating. Others include development of the correct use of thermal gradients in the container body that not only create directional heat flow (or flux) in the container body, so removing extrusion deformation heat from the critical region in the billet immediately in front of the die entry, but also balancing heat generation with heat losses, maintaining that balance, and thus achieving stable thermal conditions during ongoing extrusion cycles. The objective being to ensure the container is capable of removing deformation heat, avoiding any accumulation of heat that overrides the element control system, and generally avoiding the need for supplementary cooling (except in special circumstances – considered below).

Container cooling.

When is it appropriate to add cooling to a container? A well designed container with optimally developed heat flux gradients (created by the smart use of temperature zone offsets, especially longitudinal offsets), plus the use of a higher conductivity steel in the container body, should be able to cope with the demands of even the higher productivity levels enjoyed in the traditional 6xxx alloy extrusion world. In

other words, in almost all cases a modern container can balance heat flow out with excess heat generated in the process, and by thermocouple modulation to control temperature in each of the control zones, and maintain the necessary thermal gradients in the container body.

However, there are instances and presslines with speciality products that produce at significantly higher than typical productivity levels, generating more deformation heat, and in need of additional cooling to avoid container and process overheating, and to avoid the need to slow down. A typical case is high productivity automotive climate control multi-hole coiled tubing in 3xxx or 1xxx alloys, where to avoid liner overheating and to ensure excess heat generation is extracted, some cooling may be necessary.

Traditionally when cooling is applied to a container, spiralling grooves machined into the container body (mantle), circulate air around the outside of the liner. While air by nature is a poor conductor of heat, it is the most convenient and safest cooling medium to use. Figure 3 illustrates a typical heat balance during extrusion. Assuming the container and the die remain at constant heat, the billet heat A increases during deformation by B – the heat of deformation being the area under the force/displacement curve less the energy required to overcome container friction. Heat losses C occur due to heat flow through the container. The sum of these, i.e. (A + B) – C is the heat transported away in the extrusion. This somewhat simple approach ignores heat generated in the die which will add to the heat mass in the extrusion, but the important part of this equation in terms of the container, and design of cooling if necessary, is that C must be capable of equalling or exceeding B. (In the case of external heating elements, C may be a positive term in the equation, having a net effect of increasing the liner temperature.)
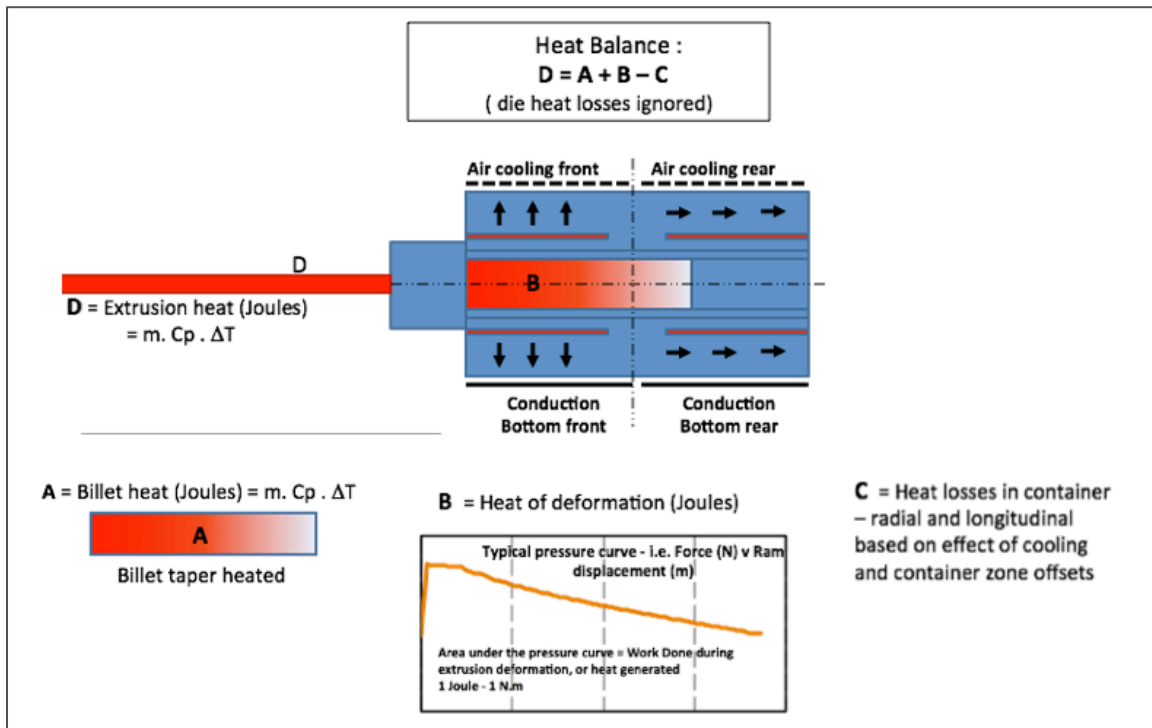

Figure 3: Heat balance during extrusion, showing the need for a container to be capable of removing the heat of deformation during extrusion.

Recognizing high productivity processes with high heat generation, and that cooling is indeed necessary, a container can be designed with external cooling of the body, rather than cooling around the outside of the liner. As cooling a liner disrupts both the radial and longitudinal heat flux through the container body, cooling the outside of the container complements it. A container design with two zone external cooling is shown in Figure 4.
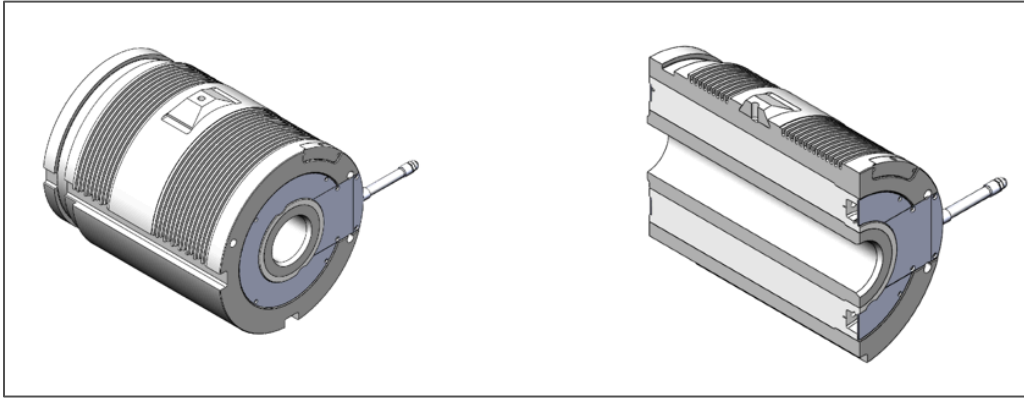
Figure 4: Two zone external cooling arrangement in a QR container – designed for high productivity microtubing extrusion.

The container design successfully removes additional heat from the high deformation process, and can develop optimum heat flux gradients in the container body by use of both longitudinal and radial offsets, generated by smart selection of container zone temperature settings.

Two-piece and three-piece multi-zone container designs.

A two-piece container consists of the container body (or mantle) with only the one-piece liner. This simpler design is adequate for most lower pressure presses, which can generally be defined as those operating at specific pressures of 690 MPa (100 ksi) or less, i.e. traditional design presses for conventional 6xxx alloy extrusion. When presses operate at higher specific pressure, it is recommended that a 3-piece assembly be used, with a sub liner (often referred to as an outer liner) generally manufactured from 4340 steel, between the container body and inner-liner to provide additional support and stiffness, thereby reducing deflection under pressure. Design of containers, 2-piece or 3-piece is adequately covered in the classical text [1].

In addition, 3-piece containers are recommended when presses are used to extrude alloys with lower flow stress alloys, i.e. 1xxx and 3xxx alloy groups, and at higher extrusion ratios. These production situations are discussed elsewhere [9] where special consideration needs to be given to the relationship of dummy block and container when both expand together under extrusion pressure. It is important to maintain a smaller clearance between the container liner and dummy block because of the higher sensitivity of these softer, lower flow stress alloys to the gap around the dummy block, and their natural tendency to back extrude over the dummy block. Therefore, in order to ensure the gap between container and dummy block is better controlled, a three-piece container with the additional sub-liner support and reduced expansion is required in these situations, along with the use of a high pressure dummy block [9].

A further situation requiring the use of a 3-piece container, and the additional stiffness, is with longer container presses. Containers in excess of 1.2m better perform with a sub-liner.

Generally, containers (2-piece or 3-piece) require four temperature control zones – two at each of the rear end and die end, one top and one bottom, as illustrated in Figure 5. Such an arrangement allows any extruder the option to select temperature offsets (top to bottom at the die end, and die end to rear end), to better control and equalize extrusion exit temperature and run out lengths with multi hole dies, and also to best facilitate the thermal gradients in the container body to optimize heat transfer away from the extrusion process.
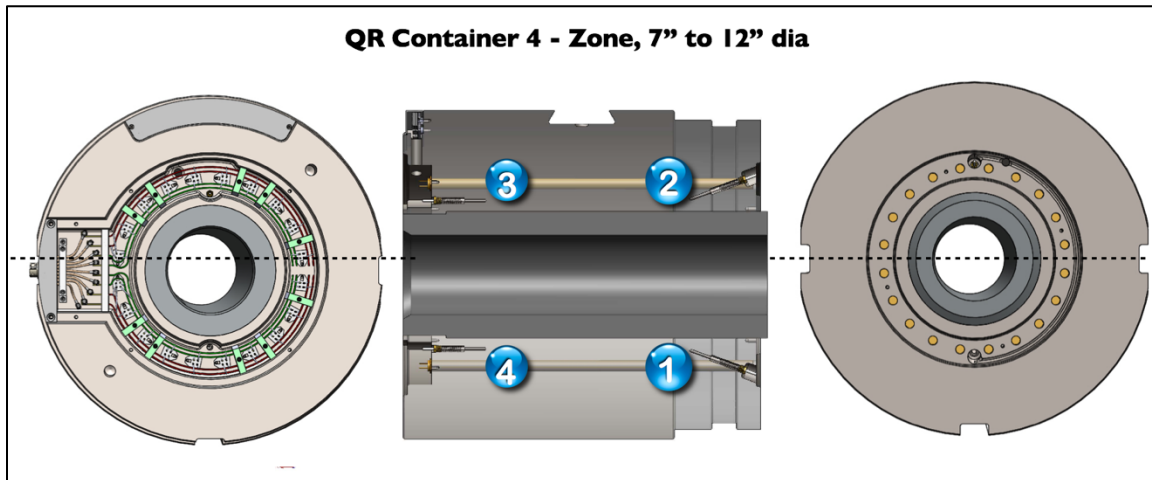
Figure 5: A 2-piece 4 zone QR container.

In certain specific instances, the bulk of the product range may involve wide complex (often multi-void) extrusions such as railcar profiles, additional control of container temperature can improve billet flow at the extreme edges of a wide extrusion. The 6-zone container shown in Figure 6 has four temperature control zones at the die end and two at the rear of the container.
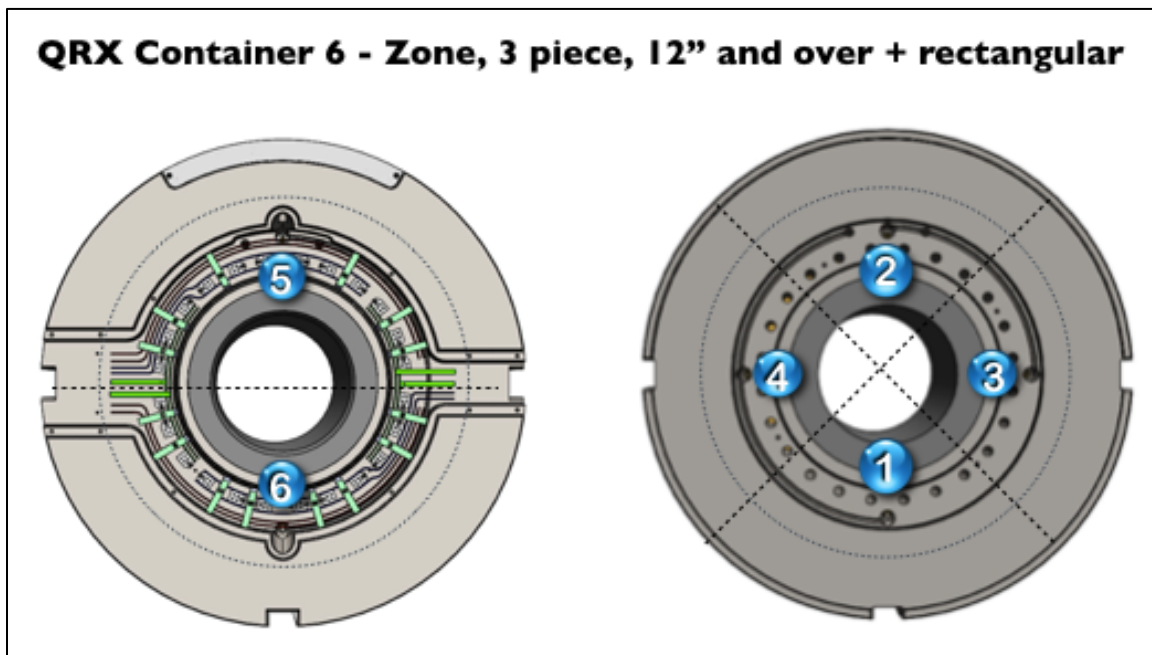

Figure 6: A 3-piece, 6-zone QR container.

3-piece container designs, can therefore minimize liner deflection by supporting the inner liner with an additional sub-liner, providing improved performance and service life of both the dummy block and liner, with high specific pressure presses, and with presses with long container length. The benefits also apply with high extrusion ratio extrusion of low flow stress alloys in the 1xxx and 3xxx series, with the added benefit that press downtime and product recovery can be improved due to reduction of blow by, and blister generation.

MODELLING:

To enable a better understanding of the container thermal challenges, modeling work was performed by Altair Engineering, Inc. utilizing both OptiStruct® and HyperXtrude® software, to study both thermal distribution and also operating stresses within both the container and the liner.

Today's modern front loading compact presses operate at higher specific pressures creating design challenges on tooling such as dummy blocks. This subject is covered in more detail in the associated paper presented in this conference [9], including the relationship and interaction between dummy block and container, that is discussed further below.

The initial modeling work considered the effect of heat up and how quickly a well designed container can reach container zone set-points after starting from a constant temperature through the container body of 350°C (662°F). With elements placed close to the liner, Figures 7 (a) and (b) illustrate that stability is reached in each zone after as short a time as 75mins – assuming the extruder is adopting offset temperature practices in the container and using billet taper preheat to help facilitate isothermal extrusion. The container zone set points used in the analysis (see Table 1), were selected as being typical of a high productivity extrusion operation. Modeling was performed on a Castool QR container - 210mm diameter liner x 1100mm liner length. The dummy block used in the modeling was the new HPR (high pressure replaceable ring) block.

Table 1: Container zone set points used in model.

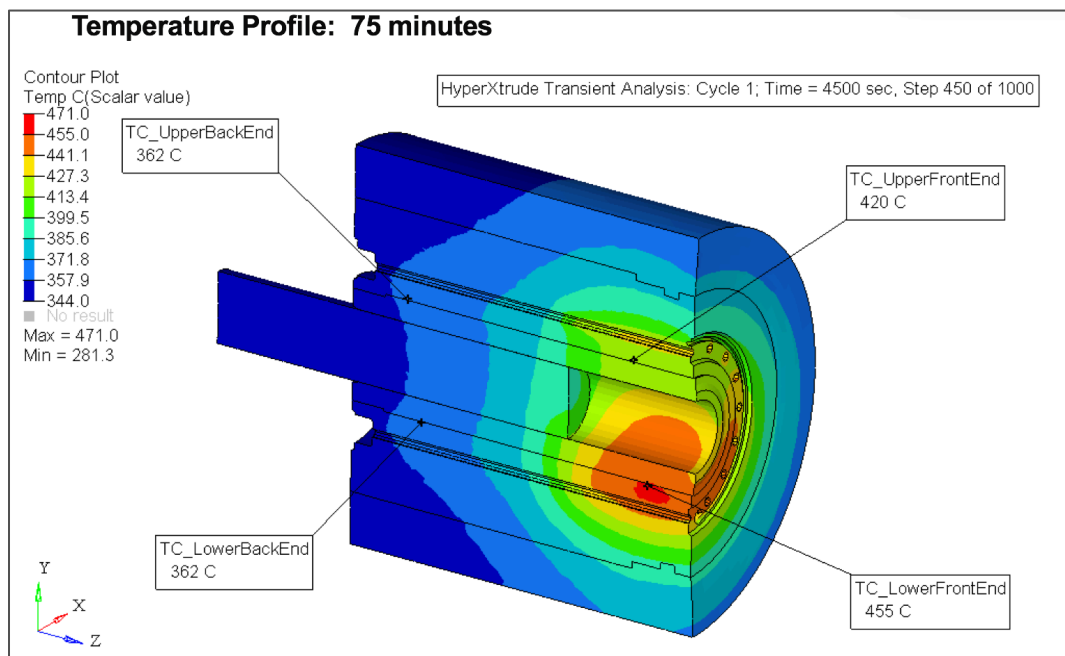| Container Zone	Set Point Temperature °C (°F)
Rear end – top	360 (680)
Rear end – bottom	360 (680)
Die end - top	420 (788)
Die end - bottom	455 (851)

Figure 7(a): Thermal distribution of a container having reached temperature stability versus zone set points after 75 mins. Heat up from 350°C (662°F).
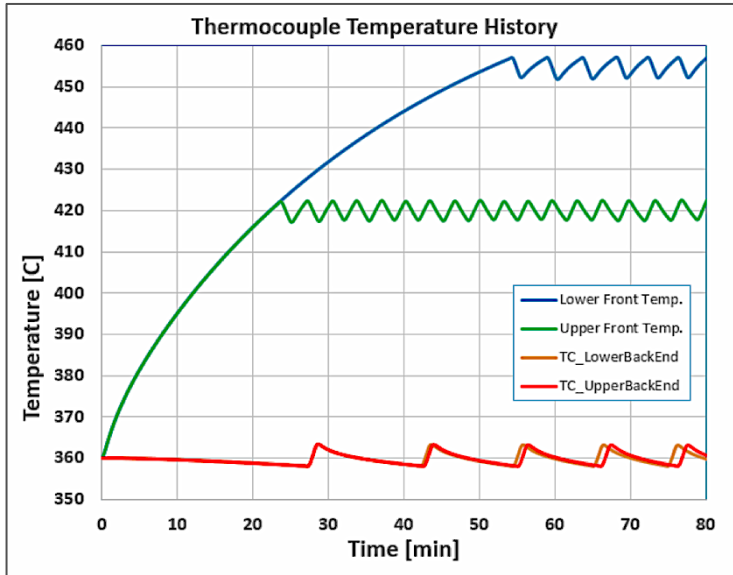

Figure 7(b): Heat up cycle times for each zone – for the container in Figure 7(a) reaching the zone set points shown in Table 1.

The adjustment time to bring this container from 350°C to desired temperatures in each zone is relatively short (note that the upper die end zone set to 420°C reached temperature in less than 25 minutes), and will therefore have little effect in terms of influencing extrusion productivity and profile dimensional stability. Indeed, the heat up time can readily be catered for by setting the required zone temperatures as little as 1.5 hours before production start up. Of course, longer time will be required if front to back temperature offsets are less, or are not used, or if the container does not have elements located close to the liner, resulting in slower response and less thermal stability.

Simulated Extrusion.

Further analysis was performed to better understand temperature distribution during extrusion. To validate the model predictions and some boundary assumptions, actual extrusion pressure curves and conditions were recorded for a 6063 4-cavity hollow alloy profile on a 25MN 8" front loading press, and compared with the model output. The billet temperature was 460°C front, 360°C rear (840°F, 680°F). The ram speed was 8.5mm/s (20 ipm), and the initial die temperature for the first billet was 460°C. Dead cycles were 16 seconds. The conditions were modeled using HyperXtrude® and the predicted pressure curves for 5 billet cycles are shown superimposed on the actual pressure curve in Figure 8, indicating good simulation, and pressure stabilization as early as the second billet.
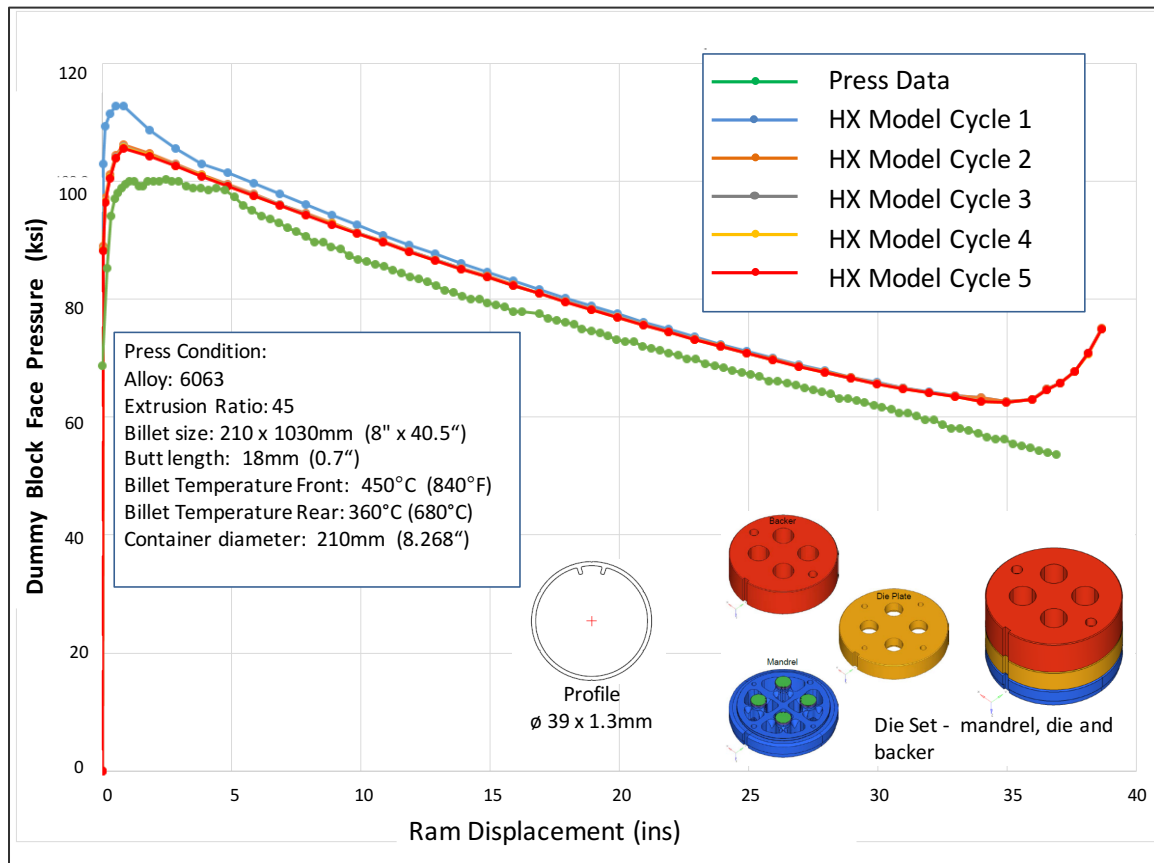
Figure 8: Dummy Block Face Pressure v Ram Displacement. Extrusion Data and Model Prediction.

Thermal Distribution during Extrusion.

Recognizing the importance of thermal stability in a container and the effect on process and product consistency, the thermal conditions in the container, along with those in the dummy block, the billet and the extrusion as it exits the die were also modeled to assess how effective and consistent container heat flux, and realisation of stable thermal conditions in the container may be.

The container thermocouple response, and the predicted exit temperature relating to each of five extrusion cycles are shown in Figure 9. It should be recognized that the container, at the start of the first billet was running at stable set point temperatures for each zone – i.e. those shown in Table 1. The die exit temperatures are the predicted temperatures at the very exit of the die bearing.
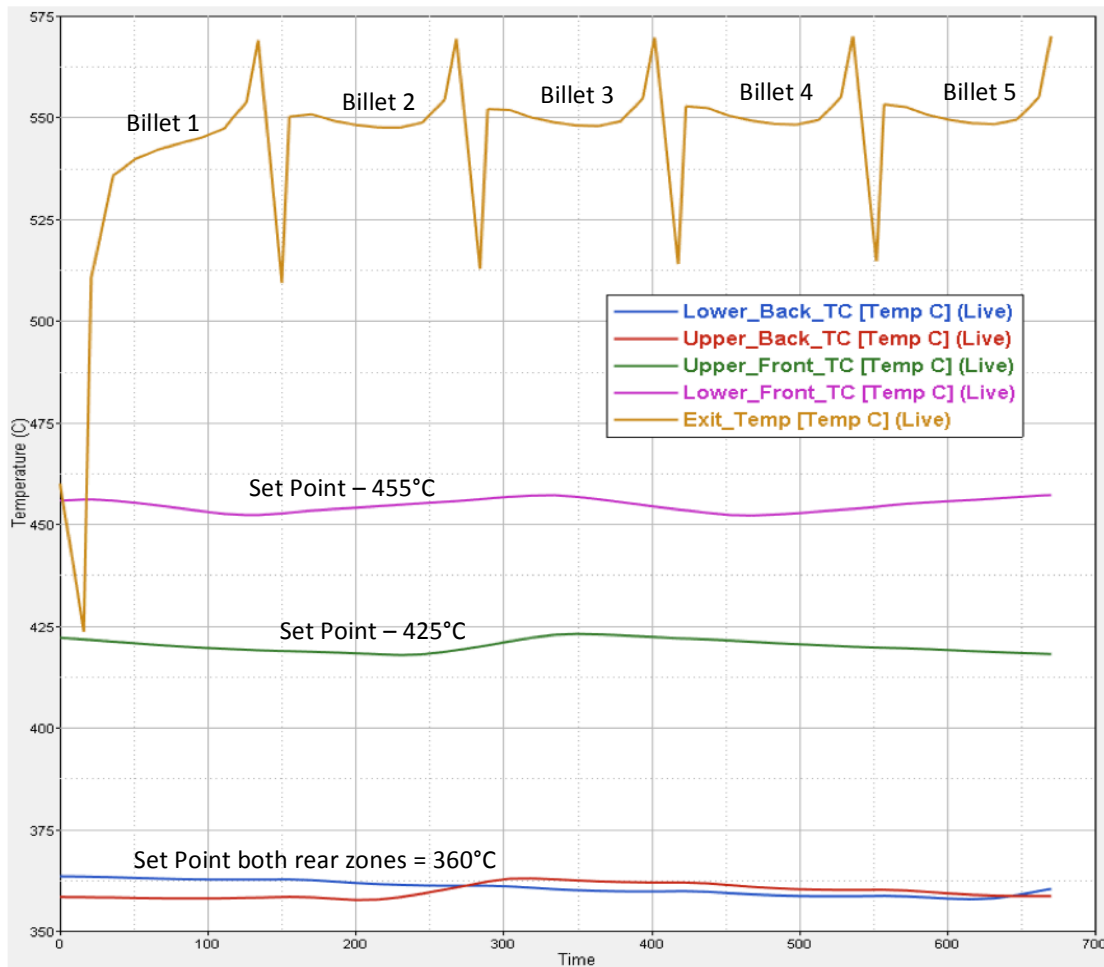
Figure 9: Thermocouple responses in each container zone, and die exit temperatures during extrusion of 5 consecutive billets.

Figure 9 shows each container zone control thermocouple switching on/off within a +/-2°C tolerance, as defined by their specification. The container therefore controls consistently and holds the set point temperature well during the 5 billet extrusion simulation. The extrusion exit temperature shows the die exit temperatures stabilizing as quickly as the second billet, supporting Figure 8 where stable extrusion pressures were also achieved early as the second billet. The rather high peak in exit temperature at the very end of each extrusion cycle, shown in each cycle as an increase in temperature of around 15°C, can be related to the very short butt length of 18mm for a 1000mm long billet. A similar peak is evident in the pressure curves shown in Figure 8, associated with a higher resistance to billet flow into the die as the remaining butt length becomes so short. Such increases in exit temperature are typically not observed in industry, however exit temperature measurements are normally taken at the platen exit not at the die, and employing butt lengths as short as 18mm for a 1000mm long billet are typically only considered for the leaner 6063/6060 type alloys, which by nature can better tolerate higher spontaneous die exit temperatures.

The following sequence of illustrations in Figure 10 shows thermal contours in the container, the billet, the dummy block and the die stack during and extrusion pressure cycle. The No. 2 billet cycle in the five billet sequence was selected to present this data, but as observed above billet No. 2 is very representative of any billet 2 through 5. Thermal contour patterns are shown at the start of extrusion, midway through extrusion, and at the end.
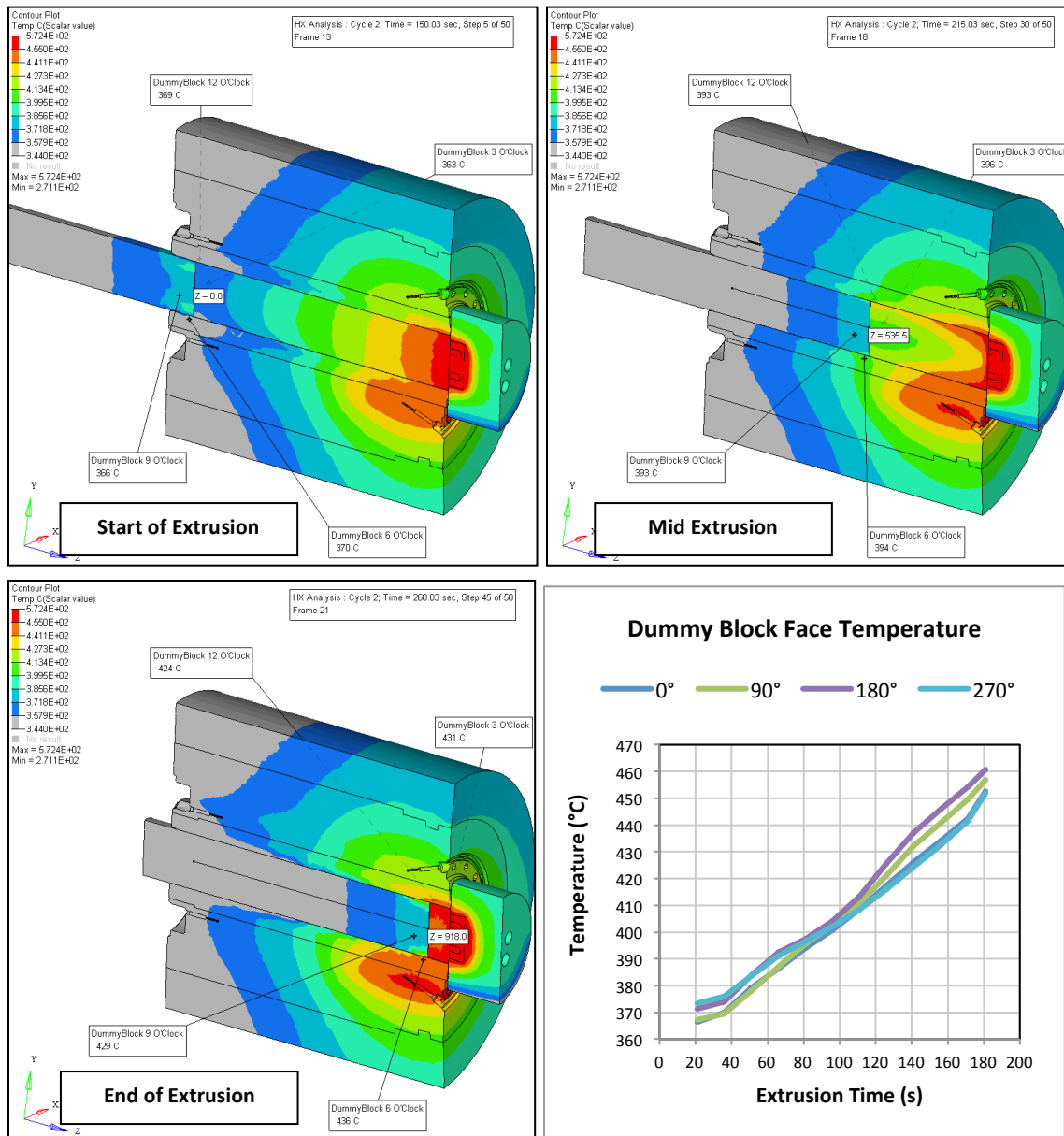
Fig 10: Extrusion Analysis Results. Temperature profiles of QR Container and HPR Dummy Block Temperatures during a simulated extrusion run - Cycle 2 of 5.

A number of features are of interest in Figure 10. Although this Figure illustrates only the second billet out of five, the container does reach stable heat gradients in both the linear and radial directions, as indicated in Figure 9. Furthermore, the container shows the higher temperature zone at the lower die end (or exit) of the container is functioning as intended. This deliberate higher temperature set point, to compensate for heat losses into the die cassette and die slide, can be seen to develop a consistent and even radial temperature distribution in the die assembly. There may be a slightly higher temperature toward the bottom, but not significant. This is better indicated in the dummy block temperatures taken when viewed the face of the dummy block at 0°, 90°, 180° and 270°. Toward the end of the extrusion cycle, where it can be assumed the dummy block face temperature will be very similar to die face temperature (and to the butt temperature), the bottom 180° position increases between 3 and 8°C above the other positions. Nevertheless, the role of a "top to bottom" offset – in this case a 30°C offset - is confirmed to help equilize temperature of billet flow through the die, and therefore contribute toward equalization of run out speed and length with multi-cavity dies, and improve recoveries.

The longitudinal, i.e. front to rear, nature of heat flow is also a positive feature in that it compliments radial heat flow due to the additional temperature offset between front and rear zones of the container. Of further interest is the effect the top to bottom temperature offset at the die end of the container has on exrusion exit temperature, which is illustrated in Figures 11 & 12.
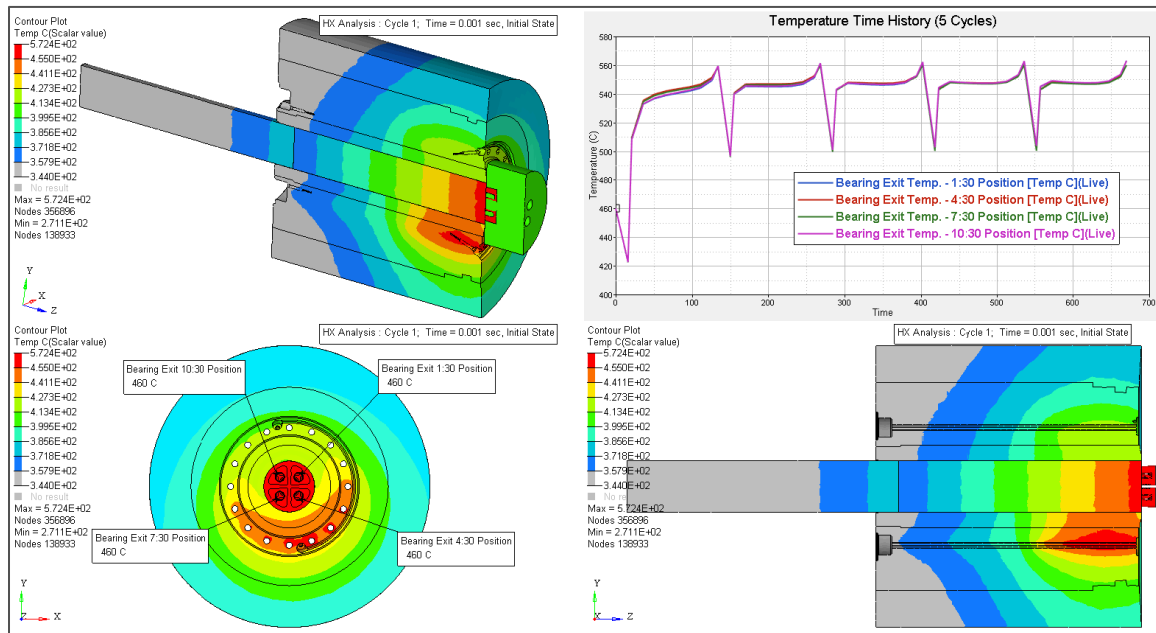

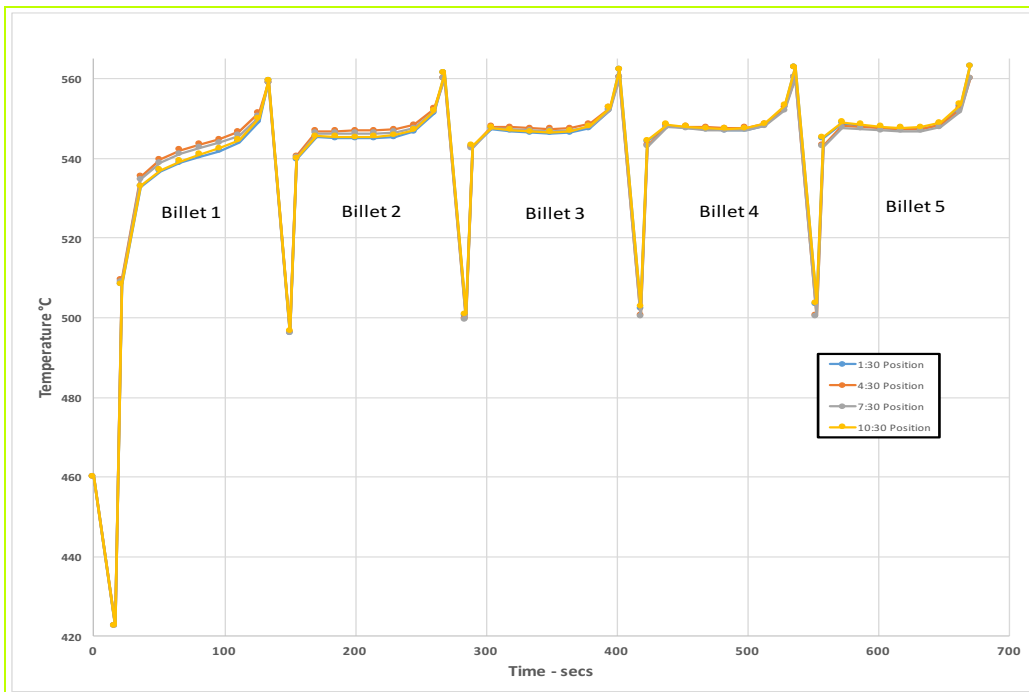Figure 11: Die Bearing Exit Temperature for each of the 5 consecutive extrusion cycles modeled.

Figure 12: Improved view of the Die Bearing Exit Temperatures

It can be seen in the graphical representation better illustrated in Figure 12, that the four die exit temperatures, recorded at the clock positions as indicated, vary little. Detailed review of the data indicates that during extrusion of billet 1 the maximum variation across the four cavities is 3.5°C, with the lower 4:30 and 7:30 positions the hottest, and the top two cavities colder. By billet number 3, the exit temperature across all cavities is essentially equal, with a maximum variation of no more than 0.6°C.

The well designed container temperature profile can therefore be stable, and if the zone temperature settings and offsets are correctly selected, die exit temperature variation, and run out variation can be minimized.

Stresses in the container.

Stress levels were modeled and studied in the container and in the dummy block. Dummy block stresses are covered in more detail in the other paper presented in this conference [9]. Stress levels in the container at the start, midpoint and the end of an extrusion cycle are shown in Figure 13.

(a) Start of Extrusion
- i.e. max pressure.

(b) Mid point of Extrusion.
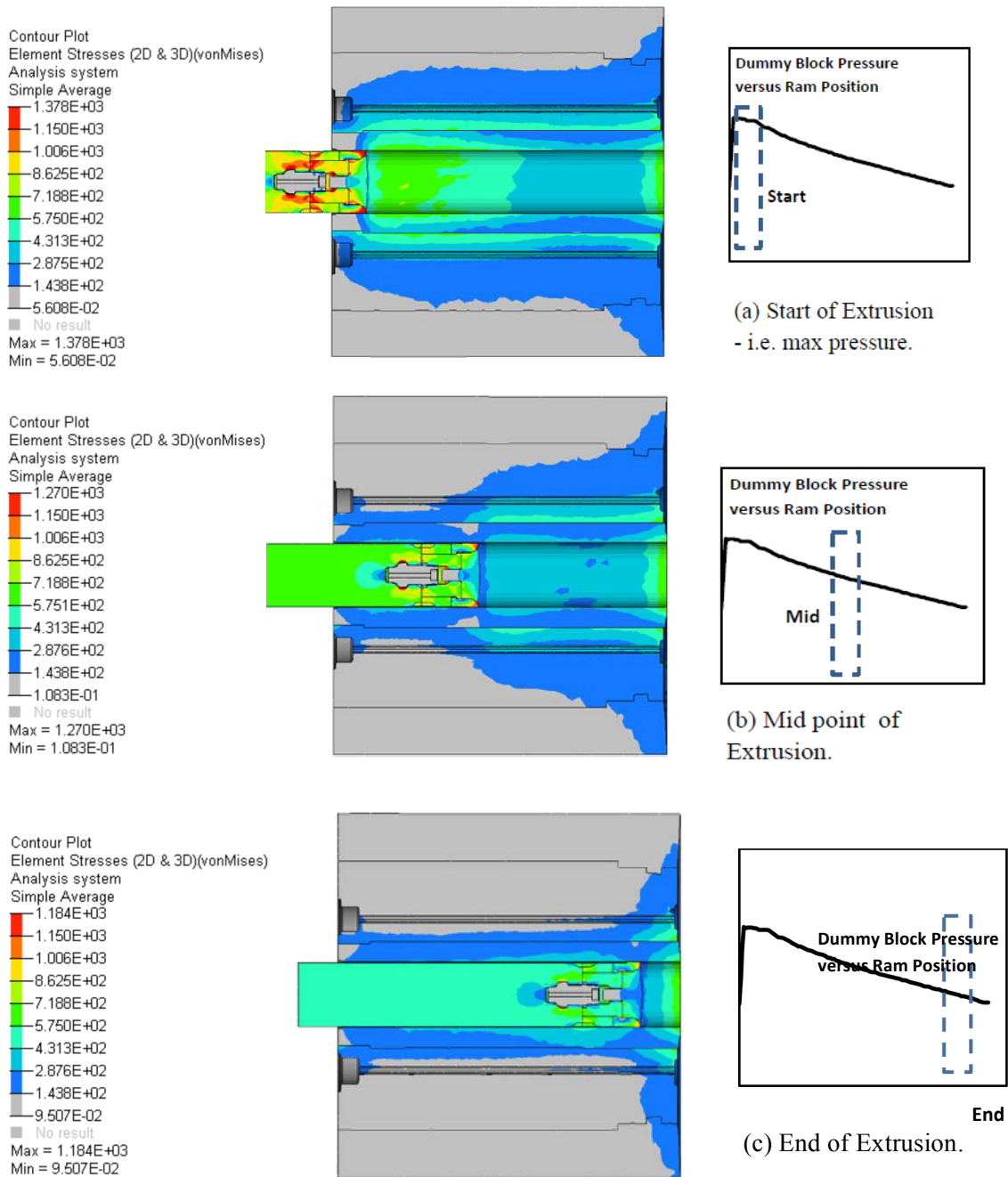
(c) End of Extrusion.

Figure 13: Stress contours (Von Mises) in QR container and HPR dummy block during extrusion.

Figure 13 shows relatively low stress levels in the liner, higher at the start of the pressure cycle but at all times no more than 719 MPa (104 ksi). In the container body (or mantle) maximum stresses fall to around 575 MPa (83 ksi). In the region of the elements, the stresses are lower at a maximum of 431 MPa (63 ksi) and at container mid radius no more than 287 MPa (42 ksi) but generally less than 144 MPa (21 ksi).

By studying these stress levels in conjunction with the operating temperature contours shown in Figure 10 it is possible to compare with steel elevated temperature property data and select the most appropriate material for both the liner and the container body. While H-13 (DIN 1.2344) has been the most common steel to use for the liner, it remains the most appropriate having sufficiently high yield strength and toughness at the liner operating temperatures. However, this work illustrates that the combined temperature and stress levels in the container body, allow consideration for the use alternate steels with higher thermal conductivity, such as 4340.

The stress level inside the container body at the maximum extrusion pressure reaches 575 MPa (83 ksi). At 427°C (800°F), 4340 steel tempered to 34 HRc has a yield strength of 700MPa (102 ksi) and UTS of 861MPa (125 ksi). Therefore, the use of a 4340 steel at 34 – 35 HRc, would provide enough strength to withhold this extrusion pressure with a 50% safety factor. Additionally, 4340 steel has a much higher toughness value than the common steels of choice for container body, i.e. 1.2343 or 1.2344. 4340 steel at 35 HRc, has an average Charpy V-notch toughness of around 110 J at room temperature, while H-1.2344 (H-13) at room temperature has an average Charpy V-notch toughness of around 24 J. Having better toughness, crack initiation with 4340 steel is more difficult under mechanical and thermal pressure. In addition, a crack propagates in 1.2344 at about 10^{-5} mm/cycle under repeated loading. A crack propagates in 4340 at about 10^{-6} mm/cycle. Under the identical pressure loading, the crack inside 4340 will propagate 10 times slower than 1.2344. In other words, it will take about 10 times more repeated loading for 4340 to create the same crack as 1.2344. This is also reflected in the fatigue limit of the materials. 4340 has a fatigue limit around 795 MPa while 1.2344 has a fatigue limit around 350 MPa.

In conclusion, 4340 is a preferred material with increased toughness and fatigue resistance therefore better able to accommodate the applied stress levels, and cyclical loading conditions in a container body. 4340 has the added benefit of higher thermal conductivity at 42 W/m.°K compared to either 1.2344 or 1.2343 at 24 W/m.°K, therefore better capable of quickly developing stable thermal gradients, and better able to extract heat from the critical deformation zone inside the container during extrusion.

Effect of pressure and temperature on the liner bore during extrusion.

During the extrusion of a billet the maximum hydrostatic pressure at any point in the stroke is adjacent to the dummy block. The result is that the diameter of the internal bore of the liner is at a maximum at this point. Figure 14 shows the calculated internal bore diameter at three positions (a) the start of extrusion, (b) mid and (c) the end of the extrusion stroke. Total expansion (thermal and mechanical) can be seen as a "wave" effect as the ram advances during extrusion of every billet.

(a) - At Start of Extrusion

(b) - Mid-way through Extrusion
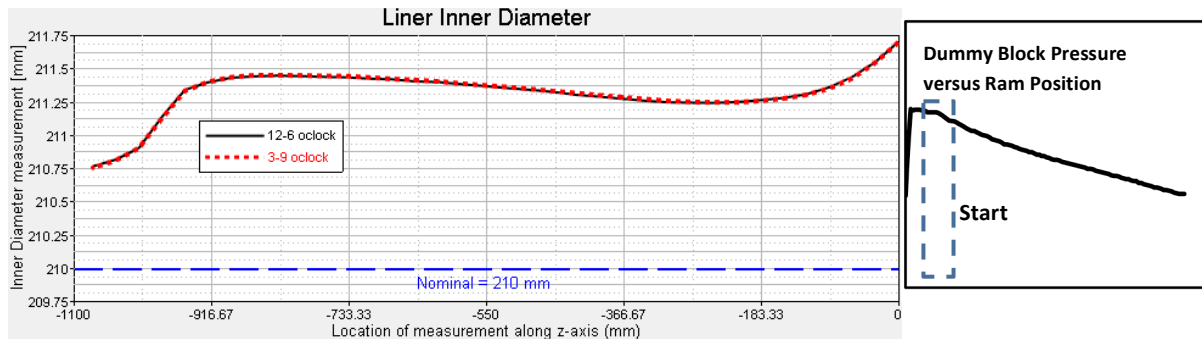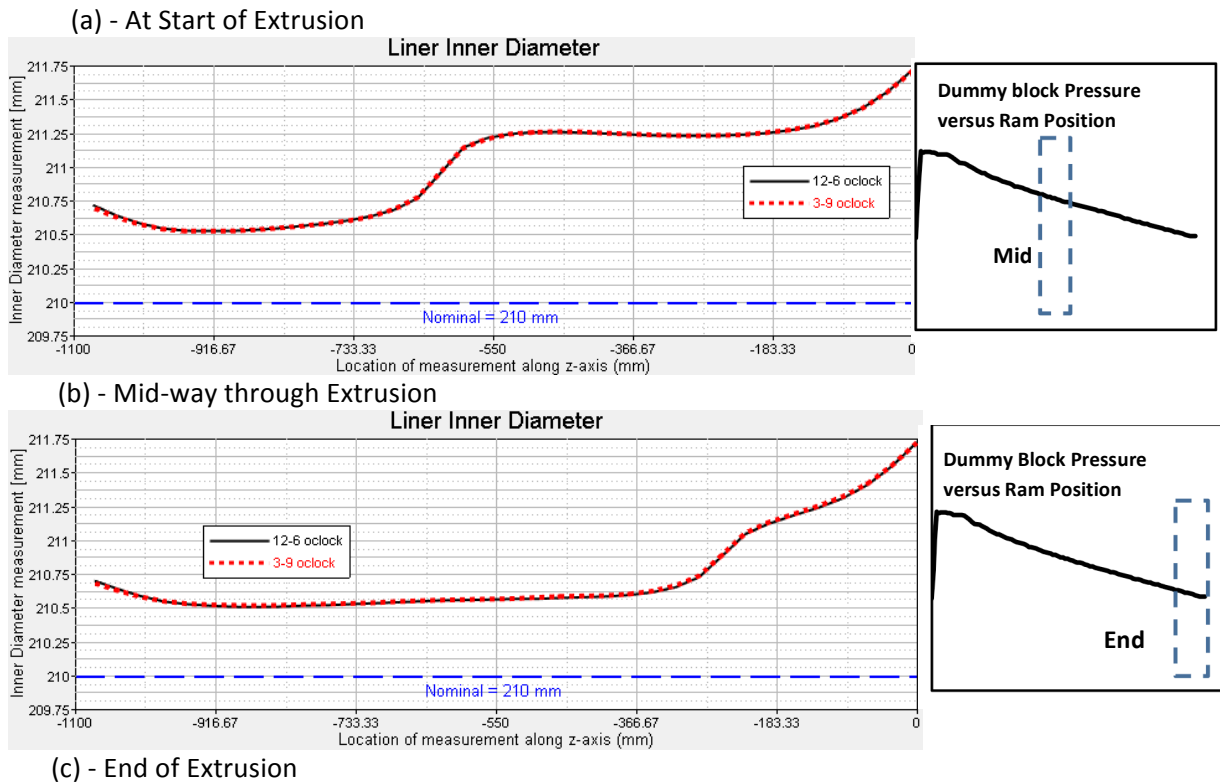

(c) - End of Extrusion

Figure 14: Change in container liner diameter (thermal + mechanical) along the container length and during extrusion.

At the beginning of extrusion (Figure 14-a), the liner diameter increases by 1.5mm over the starting cold diameter. This occurs adjacent to the dummy block and is about 1.25mm over the rest of the billet. At the centre of the billet the expansion is 1.25mm and at the end (Figure 10-c) is 1.0mm. One may conclude that this variation in diameter may be a problem in relation to maintaining a constant clearance between the liner and block.

However, the behaviour of a container expanding under variable applied pressure during an extrusion cycle, must be considered along with the respective behaviour of the dummy block under the same extrusion cycle and pressure conditions. To understand this better, the expansion of both the container liner and the dummy were modeled under the standard extrusion conditions and with the die/profile aforementioned. The expanded diameter data is compared with the original (no pressure, cold) diameters of both the liner and dummy block in Figure 15. Taking the difference between the two expanded diameters under extrusion temperature and pressure, and dividing that difference by 2, the thickness of the aluminum skin left on the container liner can be calculated. This skin thickness is also plotted in Figure 15 and shown on the secondary vertical axis.
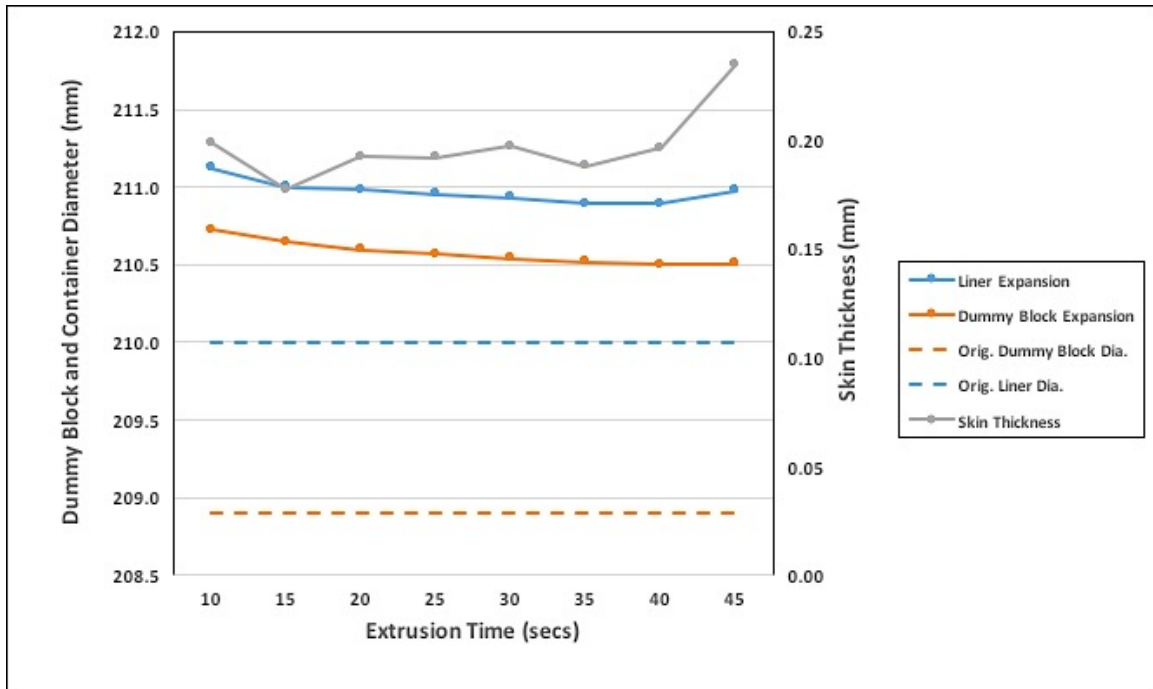
Figure 15: Expansion of both container liner and dummy block during an extrusion cycle. Also showing the generated skin thickness.

The effect of friction on the dummy block component was considered in the dummy block studies [9], and found to have an influence on dummy block expansion. For example, a purely frictionless dummy block will expand under load approximately 60% more than one where the moving component parts have a more realistic coefficient of friction where $\mu = 0.75$ The data in Figure 15 assumes a realistic friction coefficient of 0.75

Therefore, although the container liner and the dummy block each expand to varying extents during a total extrusion pressure cycle, the expansion of both lessens as the applied extrusion pressure falls throughout the cycle. Interestingly, the difference between expansion of the container liner and the dummy block remains remarkably constant throughout, resulting in a relatively constant aluminum skin thickness on the liner of around 0.18mm (0.007"). Maintaining a shallow aluminum skin thickness on the container liner wall can help minimize extrusion surface quality issues, associated with billet skin inflow. This is discussed more in the following section.

METAL FLOW IN THE CONTAINER:

It is well known that the surface of extrusion billets has a structure very different from the bulk. It includes a layer called the inverse segregation zone and it also has a surface oxide film. It is an inevitable part of the direct hot extrusion process that some of this material will enter the extruded profile by nature of coring, thereby occurring near the end of the extruded length. Because of the nature of the flow, this material forms an annular surface between the centre and surface of the profile. This layer plays no part in the generation of the surface and it is therefore acceptable for non-critical profiles. With "structural" profiles, this material is unacceptable and should be scrapped in profiles that require sound mechanical properties. The amount of scrap can be as high as 15% of the billet weight.

Work stretching back to the original paper of Lefstad et al presented at ET 1992 [10] and continued by others including the current authors, Dixon and Jowett [11-16] has studied the flow of the billet surface layers into the extrusion. The early work on modelling billet skin inflow [11] showed that the effective thickness of the skin is the sum of that left on the liner wall from the previous billet and the current billet

inverse segregation layer. The paper by Reiso et al at ET 2012 [17] confirmed the conclusions that the material on the liner bore is detrimental to the quality of the profiles.

Managing the material on the liner wall.

It is not intuitively obvious that the material left on the liner wall, that is the skull (or skin), should be as thin as possible. One might argue that to leave a thick layer of material on the liner will trap the billet skin material and stop it entering the die and flowing into the extrusion. This might well be the case for a very small order, but the results of Dixon, Reiso and Jowett show that in an equilibrium state in the middle of an order there is a buildup of oxide and intermetallics both on the liner surface and in the die and this material will eventually enter the extrusion. To quote Reiso, "if the clearance is large, it opens up the possibility to accumulate the billet surface material both on the liner wall and in the die". This will eventually flow into the extruded profile through both flow paths (type 1 and 2 as shown in Figure 16 below). Accumulation of skin material from the liner wall also occurs in the pockets and ports of dies which means any inverse segregation and oxide skin will eventually move into the extruded profile. This was reported in ET 2012 [18] and it was shown that streaking defects were influenced by the residual material from preceding billets (in other words the clearance between the liner and fixed dummy block).
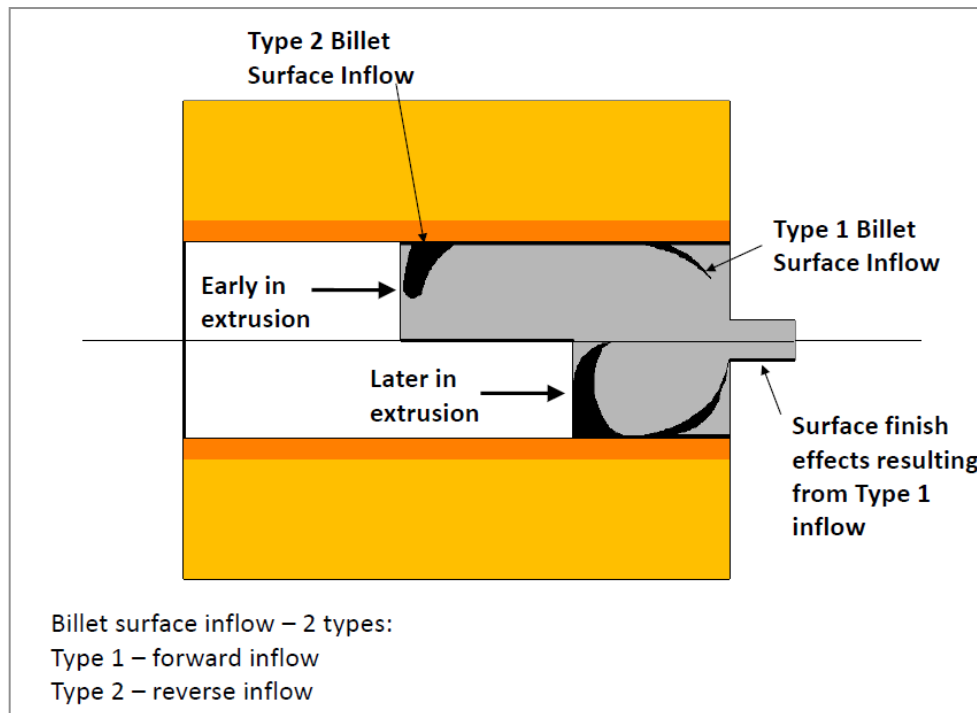

Figure 16: Showing the distinction between type 1 flow (over the dead zone) and type 2 flow (coring or back end flow).

A small clearance between the container wall and the dummy block will reduce this accumulation in the die. The clearance should therefore be made as small as possible without direct contact between the dummy block and the liner wall.

Management of this skull is critical to producing high quality extrusions. The simplest way to check the dummy block to liner clearance is to use a clean-out block and weigh the skull that is produced. Ideally the clean-out block should be of the expanding type which can be safely used cold. This will give an idea of the average clearance top, bottom, left and right, but it will not tell you the variation along the container length. Figure 17 shows various clean-out blocks and skulls.
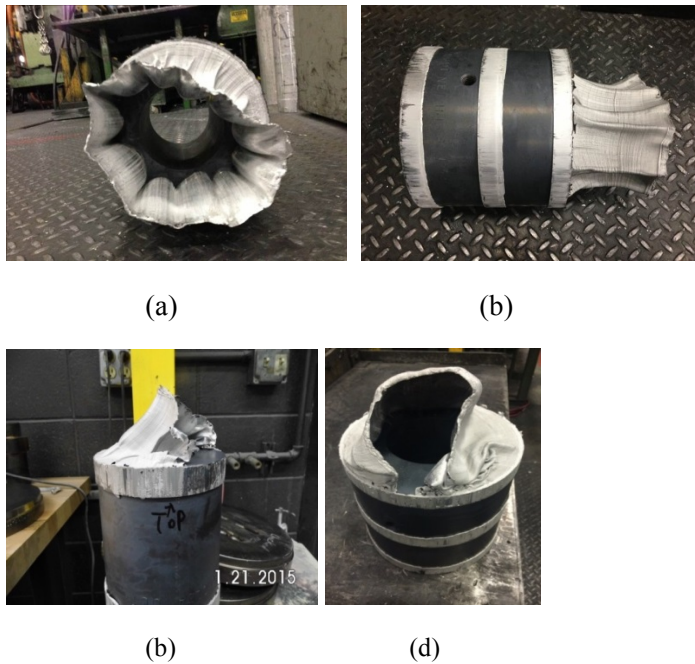
(a)   (b)

(b)   (d)

Figure 17: Showing various clean-out blocks and skulls.

Figures 17 (a) and (b) show a uniform skull which demonstrate the stem and liner are well lined up. Figure 17 (c) and (d) show uneven skulls which show the dummy block is not central in the liner. In addition, it is obvious that skull in (c) is far thinner than (d) which would be quantified by weighing and indicative of a difference in clearance. Regular use of a clean-out block including weighing will tell a smart extruder if the alignment is good and whether the block is wearing or not expanding correctly, or if the original clearance between the container and dummy block was designed optimally. In order to measure the actual liner / dummy block clearance at any point on the liner an aluminum film thickness gauge should be used whenever a container is removed for reline.

Relationship between the liner bore diameter and the size of the expanded dummy block – and their interaction.

"The dummy block must repeatedly pass smoothly through a perfectly round and straight container, while maintaining a constant clearance between itself and the liner. This produces a controlled skin of alloy residue on the liner wall, making it able to clear that skin during retraction" [19].

Naturally this clearance will have a minimum value because of the possibility of direct contact between the dummy block and liner surface. The approach of minimizing the clearance also raises the issue of the control of the dimensions of the liner bore diameter and the unexpanded and expanded dummy block diameters and how this clearance changes from front to back of the push and from billet to billet. This naturally puts a tight requirement on the alignment of stem, dummy block and container. It is clear that a poorly designed dummy block or ones that are worn or not functioning correctly will have a variable clearance with the liner bore. This allows accumulation of the billet surface layers from sequential billets on the liner surface. In the same way a washed out liner can "collect" more billet skin which can be introduced to following extrusions and produce accentuated type 1 and type 2 flow.

The expanding dummy block [9], has several functions; it has to expand under pressure to stop the flow of metal past the block land; it must contract on release of pressure allowing air to escape from the stem end of the liner, and it must leave the minimum aluminum skin in the liner wall so that defects into the extrusion are minimized. An ideal skin is as thin as possible, not too thick that backward extrusion (or blow-by) over the dummy block may occur, but also not so thin as to allow the steel block to scrape along the liner internal bore and damage the liner. It is one of the functions of the container liner internal surface

that its diameter relates to the fixed block taking into consideration the expansion and contraction caused by the variation of pressure and temperature along the length of the liner and from billet to billet.

But how should that initial clearance between dummy block and liner be designed to cater for different alloy extrusion, and different extrusion conditions of temperature and extrusion pressure? Clearly, no extruder is willing to keep changing a dummy block at every alloy change or whenever the extrusion conditions change from die to die. But realistically, that is not necessary. However, some plants produce speciality products most, if not all, of the time and a custom designed dummy block with an adjusted and optimum initial clearance may be the correct approach for a successful relationship between container and dummy block. Most times, a traditional 6xxx alloy extrusion plant operating typically with the common alloys ranging from lean 6060 type to higher strength 6061/6082 alloys, and operating in the common extrusion ratio range of between 30 and 80 most of the time, will successfully operate with a standard design of dummy block. However as mentioned earlier, and necessary for today's high specific pressure front loading presses with longer billet length capability, a special high pressure dummy block may be required. Nonetheless, that high pressure dummy block when used with the traditional 6xxx alloys in a typical extrusion ratio range, will be a standard high pressure dummy block. However, high ratio extrusion of speciality products such as microport heat exchanger tube in 1xxx and 3xxx alloys – alloys with significantly different flow stress characteristics than any of the 6xxx alloys, and by nature extruding high ratio products under high specific pressure conditions, will require a custom dummy block with reduced initial clearance to avoid the risk of backward extrusion (often called blow-by) over the dummy block. At the other extreme, dummy blocks for extrusion of hard aerospace alloys in the 2xxx and 7xxx alloys, and dummy blocks for some indirect extrusion presses will also need to be custom designs. What is clearly evident is that to provide the correct dummy block for a given operation, understanding the expansion behaviour (thermal + mechanical) of both the container and the dummy block, and how they move together, is important for ongoing trouble free success.

PRACTICAL IMPLICATIONS RESULTING FROM THE DEVELOPMENT OF A THERMALLY STABLE CONTAINER:

Container Temperature Offsets.

Having discussed the benefits of smart selection of temperatures offsets, how can a user of a well designed container select the zone temperature settings to best optimize the process? Simply stated, a longitudinal offset, i.e. the difference between the die end container zone, and the rear end zone, should be no less than the maximum taper used on any billet. As typical billet preheat tapers are in the order of 10°C/dm (7°F/inch), to realise isothermal extrusion at constant ram speed, an extruder when developing a die recipe will develop the correct taper for the die and best ram speed to achieve a near constant extrusion exit temperature. From the range of recipes used, the extruder can best select the most appropriate longitudinal offset in the container zone settings, recognizing that a large taper of (say) 120°C will encourage more heat conduction along the container from front to back and help optimize the process. It might be feared that a large longitudinal offset in the container may contribute toward chilling the rear end of the billet, but generally the residence time of the rear of the billet in the end zone of the container is short, and the effect on billet temperature is in reality negligible. Care should be taken recognizing that large container longitudinal offsets may influence the thermally driven diameter of the container liner, however the modeling confirmed that the difference in the thermally increased diameter of a 210mm container liner with a longitudinal offset of 95°C is considered insignificant at less than 0.2mm. Clearly the container offset settings depend on the thermal characteristics of the process itself – which in turn are driven by extrusion ram speed for the die and the die extrusion ratio – or essentially the additional heat generated during the extrusion cycle. The offsets will differ depending on each die, and common container settings may be developed to best suit the a range of dies used. However, for high volume dies it is worthwhile developing optimum container offset settings for each high use die recipe.

With the vertical offset between top and bottom zones at the die end of the container, a container capable of extracting heat and having a high enough thermal conductivity to do so, will operate well if the die end settings are set so the die/bottom zone is the same as the billet temperature, and the die/top zone set 30°C lower. This provides a good starting point and will work well in most instances. The need for a

top/bottom offset at the die end becomes evident with multi-hole dies that are subject to run out variations, in terms of speed and run out length. Normally the top holes run faster, resulting from heat conducting from the bottom of the die into the die cassette, the die slide and the press frame. Employing a vertical offset increases the lower zone temperature, and compensates for these heat losses. While an offset of 30°C is reasonable and has been shown to work well in most instances, productivity for some high volume dies will benefit from developing a custom offset by trial. For example, on a 7" press with a 760mm long billet, a 4-hole die with up to 5m difference in targeted 30.5m run out length, improved to less than 0.5m difference by increasing the top/bottom offset from 25°C to 50°C.

Energy Consumption.

One of the most significant benefits of the afore described heating approach for a thermally stable container is the large reduction in power consumption due to the location of the heating elements near the liner and the absence of any direct heating of the outer parts of the container or mantle. What is difficult to understand is why any other heater location would be considered. An added advantage of a container with a cool outside of the container is the reduction in ambient temperature in the area around the press. Energy consumption has been tracked for a number of different container heating arrangement (element location) and the findings are summarized in Table 2, showing a selection of comparative energy data for a QR container with elements located close to the liner versus external elements and versus elements at mid container body radius.

Table 2: Energy consumption data for a variety of container heating approaches.

Energy Consumption (kW/hr)			
7" Container		10" Container	
External Elements	Elements close to liner	Elements at mid body radius	Elements close to liner
50	32	82	53
94	34		

Table 2 shows that a QR type container container uses between 36% and 64% less energy compared to a container with external heating, and uses 36% less than a container with elements at the mid radius position of the body.

Container Life and Relining Frequency.

The mantle and sub-liner are under repetitive mechanical stress and thermal stress, and accordingly the materials eventually start to degrade.   Therefore, extrusion conditions, notably pressure and temperature dictate life expectancy of the container body and sub-liner.   Typically, bodies (mantles) are expected to perform at least 5 – 10 year before replacement is necessary. Sub-liners (outer liners) should last at least 5 – 10 year, while a liner generally requires replacement every 12 – 18 months, predominately due to wear.

CONCLUDING REMARKS:

A thermally stable container is probably the key component of an efficient extrusion press. It can have such an influence on the process in terms of the following:

1. Helping control die temperature, and compensating for die temperature losses.
2. A vertical temperature offset between the top and bottom zones at the die end of the container, can reduce or eliminate run out variations, or dimensional variations between top and bottom holes in a multi-hole die.
3. A vertical temperature offset between the top and bottom zones at the die end of the container, can reduce dimensional issues with high vertical aspect shapes, by improving consistency of flow between top and bottom ports, or top to bottom regions of a feeder.

4. Thermal stability of a container is improved by location of the elements close to the liner.
5. Conduction of heat is improved in a thermally stable container by use of both a higher conductive steel body, and the use of a longitudinal offset which helps effective removal of deformation heat from the high deformation zone of the billet immediately in front of the die.
6. The modeling has been invaluable in better understanding what best contributes to developing a thermally stable container design.
7. Modeling confirms the use of 4340 as an effective steel for container body use, and that 4340 steel in addition to having superior thermal conductivity, is capable of meeting the elevated temperature in service stresses, and has superior toughness and fatigue resistance compared to other steels commonly used today.
8. Thermally stable containers can be customized to meet the specific needs of high productivity extruders producing heat exchanger and automotive climate control tubing in 1xxx and 3xxx alloys, by introducing external cooling to the container body, the use of a sub-liner and by controlling the clearance between the dummy block and container.
9. Further customization can occur for containers of extended length, and containers with additional die end zone temperature control for wide (e.g. railcar) extrusions.
10. Modeling of a container both during heat up, and during simulated extrusion, helped develop a much better understanding of the actual thermal gradients present in a number of extrusion, and container design scenarios. Much of that data is contained in this paper.

Along with the findings in this paper and in the associated dummy block paper presented at this conference [9], it is clear a container and dummy block can be designed to operate together and expand and contract in close harmony to produce a consistent skin thickness on the container liner surface thereby minimizing the risk of back extrusion of billet over the dummy block, minimizing the risk of blister by ensuring an effective burp cycle and release of entrapped air, minimizing billet surface flow onto the surface of the extrusion, and in turn, ensuring reduced equipment stoppages/downtime, improved container and dummy block life, improved extrusion recovery and improved productivity.

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