Closed-loop Isothermal Extrusion

ABSTRACT-- Over the last several years, a number of practical approaches have been made to achieve isothermal extrusion. The traditional approach is to try to load billets with a very well defined temperature distribution into the container to obtain isothermal extrusion. Another way is to establish a closed-loop on-the-fly control between a highly reliable infrared pyrometer measuring the temperature of the extrudate, and the speed of the ram controlling the friction between the billet in the container and the container itself. This paper will discuss the advantages and shortcomings related to these approaches as well as the technical and practical requirements to establish reliable closed-loop isothermal control systems. Improvements of productivity and scrap obtained with a state of the art closed-loop isothermal control system called OPTALEX will be reported.

INTRODUCTION

Isothermal extrusion has been a desired technology during the last two decades, but technological constraints prevented availability of practical isothermal control systems for aluminum extrusion presses.

One bottleneck was the ability to measure the temperature of the profile. Another bottleneck was to develop stable and fast reacting closed-loop control systems matching all the different extrusion presses in operation.

Few systems utilizing different technical approaches are now available in the marketplace to achieve isothermal extrusion.

Advantages and shortcomings of a closed-loop system and systems optimizing billet temperature and extrusion speed are discussed in more detail.

Specific improvements obtained by users of the OPTALEX closed-loop isothermal control system are reported.

ISOTHERMAL EXTRUSION FUNDAMENTALS
Conventional extrusion

With a conventional open-loop- or closed-loop speed control the extrusion will follow a horizontal line at the extrusion limit diagram on Figure 1. Without taper heating of the billet the temperature of the profile will gradually increase throughout the push cycle time due to friction between billet and container.

A cold billet will reflect low extrusion temperatures, and a hot billet will reflect high extrusion temperatures.

To avoid pick-ups, tearings and even surface melting by the end of the push cycle caused by very hot billets, most press operators will set the constant ram speed low.

Isothermal extrusion

Isothermal extrusion based on reliable measurements of the profile temperatures and a well performing control system will follow a vertical line at the extrusion limit diagram on Figure 1.

Assuming the control system will reduce ram speed when the temperature of the profile is higher than the optimal set-point temperature, and increase ram speed when the temperature of the profile is lower than the optimal set-point temperature, the productivity improvement is obvious. And a higher average extrusion speed can normally be obtained without jeopardizing surface quality.

According to the schematic extrusion limit diagram very substantial productivity improvement will be obtained. But in reality the particular die being extruded sets the limit. This reflects a practical constraint or limit for the productivity improvement, which can be obtained, but it also reflects a challenge to die shop management.

On top of obvious productivity improvements obtained, extrusions at constant temperatures provide profiles with better tolerances and more uniform metal hardness.

During billet preheating Mg₂Si particles will precipitate in the alloy. During extrusion a number of the needle particles will dissolve again. The higher the temperature is chosen, the less the number of remaining needle particles will be, and consequently higher profile hardness will be obtained.

The massive Mg₂Si particles in the alloy will not be dissolved during extrusion.

So seen from a metallurgical point of view isothermal extrusion offer benefits as well. With a constant extrusion temperature a much more uniform metal hardness will be obtained over the entire profile. And when the temperature set-point is under the press operator’s control, it can be set as high as possible dependant on the desired profile quality, and thereby get the highest possible hardness on the entire profile.

So by definition isothermal extrusion will improve productivity, narrow down tolerances and provide a more uniform and harder profile.

However, to fully benefit from an isothermal extrusion control system, two fundamental system design requirements must be fulfilled:

1) The press operator must be able to identify the optimal extrusion temperature and max. extrusion speed for any individual die, dependent on the condition of the die when extrusion of an order starts.

2) The system must be able to maintain this reference profile temperature within narrow limits short term as well as long term. Typical within +/- 5 degree F. (+/- 3 degree C.)

WILL ISOTHERMAL EXTRUSION CONTROL SYSTEMS AVAILABLE IN THE MARKETPLACE TODAY WORK AT ALL?

Yes they will, if the control systems are really able to keep the profile temperature in a narrow window around the optimal set-point temperature.

This can be clearly demonstrated on any press, even without a well performing isothermal control system.

With a dedicated well performing fast reacting infrared pyrometer pointing at the profile it is evident, that a skilled press operator can maintain an almost constant profile temperature by carefully watching the profile temperature all the time and continuously update the normal manual closed-loop potentiometer setting on the console.

If this is done again on a similar billet but with a slightly higher set-point it will be seen, that very small change in set-point temperature causes major changes in extrusion speed.

Typically an increase of 5 degree F. (3 degree C.) will increase extrusion speed with 10 - 15% or more.
So just by hitting the maximum extrusion temperature from the very beginning of the push cycle time rather than wait until the very last part of the billet is extruded, a lot of productivity can normally be gained, if the die can cope with higher extrusion speed.

This is illustrated in Figure 2.

![Figure 2. Conventional/ Isothermal extrusion](image)

**STATE OF THE ART PYROMETES AND CONTROLS**

The “profile temperature” dilemma

Although the phrase “profile temperature” is used over and over again in this industry, there is not a common understanding of the meaning of it, probably for practical reasons.

![Figure 3. Profile temperatures](image)

As illustrated in Figure 3, any extruded profile contain any number of individual temperatures from spot to spot on the surface of the profile and in any internal spot of the profile. Only on the surface 10 individual people will arrive at 10 different temperatures, dependant on the place of measurement, type of pyrometer, duration of the measurement etc. It does not make it easier that the temperature is a function of time.

A typical square profile with a thickness of 0,25 inch. (6 mm.) has a cooling rate in forced air of app. 5 degree F. (3 degree C.) per sec. So assuming the ideal pyrometer was available to measure the precise temperature in a very small spot of the profile at a given time, we have to accept as follows:

Any reading within +/- 5 – 10 degree F. ( +/- 3 – 5 degree C.) from this precise temperature have to be considered correct given the pyrometers commercially available in the marketplace today and the methods of measuring.

Even a high quality, well handled and newly calibrated contact thermocouple need a couple of seconds to stabilize, and it will still “only” measure the ever changing temperature in one particular point with an accuracy of +/- 5 degree F. ( +/- 3 degree C.).

That opens for a lot of discussions between customers and suppliers of pyrometers, and temperature readings can all be correct in spite of major differences between the numbers.

If more sophisticated pyrometers like infrared pyrometers are used for “profile temperature” measurements, it is evident that the wobbling of a profile coming out of the platen makes the temperature reading of infrared cameras with a small target spot size questionable as illustrated in Figure 4. Keep in mind that at a given time the temperature difference in two different points of a profile can easily be 20 degree F. (10 degree C.), dependant of the shape of the profile of course.

So differences in temperature readings from that type of cameras up to 20 degree F. (10 degree C.) or more, may not reflect temperature changes at all, but merely different surface temperatures in different points of the profile at a given time.

With these problems in mind it is not surprising, that few aluminum extrusion presses today are equipped with infrared pyrometers to measure the “profile temperature”.

Lack of common understanding and shortcomings related to the conventional infrared pyrometers, has kept the “temperature stick” and questionable contact thermocouples calibrated “not long ago” as the preferred measuring tools to most press operators even today.

Nevertheless very well performing infrared pyrometers are available in the marketplace today and have been for some time. They are able
measure “profile temperatures” by taking a different approach than conventional infrared pyrometers having a very small target spot size that have to be fully covered by the extruded profile.

These redesigned infrared pyrometers optimized for aluminum extrusions have a target spot size of several inches. Only a small part of the target spot size has to be covered by profile to get a stable and repeatable reading. This reading will be just as good if not better than any other reading obtained by a newly calibrated and high quality contact thermocouples.

![Figure 4. Small/ large target spot size](image)

Permanently mounted where the extruded profile exits the platen and pointing at the center of the tunnel in the platen, these redesigned type of infrared pyrometers serve as an excellent source of “profile temperatures” to an isothermal control system.

Many small profiles coming out of multi-cavity die may wobble quite a lot but still stay in the target spot area. And a stable and repeatable temperature reading will be obtained.

One huge profile with dimensions exceeding the size of the target spot area will also provide a stable and repeatable temperature reading.

Some might argue that there is no guarantee, that the hottest spot of the profile is included in the target spot area, and that is correct.

However, the reading from the infrared pyrometer serves as a highly repeatable and highly stable temperature reference only. And as already mentioned, the reading is as good as any other reading of “profile temperature” which can be obtained by using a well performing newly calibrated contact thermocouple.

With this in mind we can conclude, that some of the infrared pyrometers available in the marketplace today, will provide highly repeatable and stable profile temperatures from single cavity as well as multi-cavity dies.

**Design requirements for the press control system**

The only practical way to increase or decrease the extrusion temperature during extrusion, is to increase or decrease the ram speed.

With the aim of controlling the extrusion temperature within +/- 5 degree F. (+/- 3 degree C.) throughout the entire push cycle time, a well performing closed-loop speed control is required for all available isothermal extrusion control systems in the marketplace today.

A substantial number of presses are still equipped with old relay systems, or open loop speed controls. To perform isothermal extrusion all have to be upgraded, and the relevant costs to do that have to be included in a project for isothermal extrusion.

A closed-loop isothermal control system measuring the profile temperature throughout the push cycle time and correcting the ram speed on-the-fly to obtain isothermal extrusion, acts in a similar way as a closed-loop speed control system, with one major difference.

Input to the closed-loop speed control comes from a speed transducer attached to the ram, correcting performance of the pumps on-the-fly to keep extrusion speed at a constant level.

Input to the closed-loop isothermal extrusion control comes from the temperature transducer, correcting pump performance on-the-fly to keep extrusion temperature at a constant level, as illustrated in Figure 5.
As suggested by Bryant, Dixon, Fielding and Macey in their article in Light Metal Age, April 1999 [1], the natural steps in achieving isothermal extrusion appear to be

1) Continuous measurement of profile temperature using optical pyrometer
2) Understand and study temperature distribution and heat balance
3) Control commercially available strategies for process control
4) Improve equipment to facilitate isothermal extrusion and
5) Automate to achieve automatic closed-loop isothermal extrusion

Although several equipment manufacturers and extrusion companies in recent years allocated substantial funds to develop control systems for isothermal extrusion few have been successful.

Control systems for closed-loop isothermal extrusion are difficult to design in such a way, that they can easily be attached to available closed-loop speed controls and match all individual presses. Furthermore these controls have to deal with dies of very different nature. From multi cavity dies with many small profiles, to dies with one very heavy slow moving profile. The main problem is to design a control system which acts fast when ram speed have to be changed to change profile temperature, and at the same time avoid serious oscillations of the ram speed.

But fast microprocessors able to deal with complicated software algorithms and years of practical product development have in recent years made it possible to offer reliable and well performing products to the marketplace.

PRACTICAL APPROACHES TO ISOTHERMAL EXTRUSION

Caused by the fact, that traditional infrared pyrometers have not been very successful in measuring the profile temperature in the past, the traditional approaches to isothermal extrusion has been:

1) Longitudinal gradient – taper heating:
   To set up a longitudinal thermal gradient in the billet just before feeding it to the press or

2) Thermo-mechanical simulation:
   To set up a speed profile for a homogeneously heated billet based on temperature measurements of the billet in the loader.

And as an alternative to these:

3) Closed-loop isothermal extrusion:
   To establish a closed-loop on-the-fly correction of the ram speed based on continuous measurements of the profile temperature

Major advantages and shortcomings of these three approaches are discussed in the following.

1) Longitudinal gradient – taper heating

As illustrated in Figure 6, taper heating will normally be achieved by either boosting one end of the billet in an induction furnace or by applying a taper to a homogeneously heated billet by means of a billet quench.

If properly designed, both methods will provide extrusion closer to isothermal extrusion than without a taper, and in some plants a general taper is applied.
more or less to all billets with some improvements of profile quality.

Major productivity improvements are normally not seen with this set up, mainly because an optimization of the profile temperature does not take place. And as previously mentioned, even small increases in profile temperature causes major improvements in extrusion speed and profile quality. To fully benefit from an induction furnace or a billet quench, measurements of profile temperatures have to take place throughout the push cycle time and an iterative learning process established.

But going back to the furnace or billet quench to adjust the taper on the billet does not solve the problem. Keep in mind that:

1) The furnace itself has a control system heavily dependant on normal contact thermocouples which can only measure the temperature within +/- 10 degree F. (-+/- 5 degree C.)
2) Transit time of the billet from furnace to loader, and from loader to container can change quite a lot
3) The press itself will not be in thermal equilibrium unless the order is min. app. 30 billets
4) The iterative learning control loop will react very slowly because the temperature setting on the furnace will only work on the billet in the furnace, while another billet is already waiting in the loader. Typical response time from 3 to 10 minutes. And this loop have to be executed several times to get the best result.

Advantages:

1) Dimensions will improve and the alloy quality of the profile will be more uniform

Shortcomings related to induction furnaces:

1) It is a very expensive solution. The investment is high, and running an induction furnace in daily operation is costly.
2) Induction furnaces put constraints on the billet length
3) An induction furnace require a lot of press downtime to install
4) The iterative learning control loop is not available and can not compensate for inadequate measurements of furnace temperatures, variations in transit time and press stops

Shortcomings related to a billet quench:

1) Installation is expensive
2) A billet quench require a lot of attention and individual programming to work properly
3) A billet quench require a lot of press downtime to install
4) The iterative learning control loop is not available and can not compensate for inadequate measurements of furnace temperatures, variations in transit time and press stops

2) Thermo-mechanical simulation of extrusion parameters

As illustrated in Figure 7, the aim of this approach to isothermal extrusion is to apply a predicted and simulated ram speed curve to a homogeneously heated billet, based on a measurement of the billet temperature when the billet is in the loader and just before it enters the container.

Furthermore the press operator has to classify all profiles according to Laue’s classification system, specifying 13 different typical “shape groups”.

This approach does not incorporate any measurements of the profile temperatures. But based on a “sample extrusion” under normal conditions this system calculates essential process parameters and predicts a maximum extrusion temperature. As the billet temperature frequently differs from the optimized reference value, the predicted ram speed curve is corrected billet by billet, dependent on the temperature measurement of the billet in the loader.

A contact thermocouple or an infrared pyrometer measures the billet temperature. In view of the dissimilarities of billet surfaces, variations of +/- 10 –
20 degree F. ( +/- 5 – 10 degree C.) from the correct billet temperature must be expected in any case.

The system can not compensate for inaccurate billet temperature measurements and the press being out of thermal equilibrium. Heat transfer from die to die ring, from die ring to backer, and from backer to bolster and sub-bolster can not be predicted as well as heat convection and heat radiation from the container.

After 30 – 70 billets thermal equilibrium of the press can normally be expected assuming the press operates continuously.

In the mathematical simulations the system does not take the actual condition of the die into account.

**Advantages:**

1) Some productivity improvements will be obtained
2) Dimensions will improve and the alloy quality of the profile will be more uniform
3) Hardware is inexpensive and the system easy to install
4) die load will not exceed maximum permissable die load

**Shortcomings:**

1) the system does not include a iterative learning facility nor a closed-loop isothermal control
2) Ram speed and maximum extrusion temperature is based on mathematical simulations. It is not checked that isothermal extrusion is actually taking place and maximum extrusion temperature obtained
3) the mathematical simulations do not compensate for the press itself being out of thermal equilibrium and incorrect billet temperature readings
4) the actual condition of the die is not taken into account

3) **Closed-loop isothermal extrusion**

As illustrated in Figure 8, this concept is simple. Reference is a set-point profile temperature controlled by the press operator dependant on the profile quality required for the actual order.

On a trial-and error basis, the press operator establishes the highest possible constant extrusion temperature the first time a new die is in operation, and keep it as the future temperature set-point. Only a few billets are necessary to optimize a new die.

Profile temperature is measured by a dedicated infrared pyrometer continuously throughout the entire extrusion cycle. If the actual profile temperature is lower than the set-point temperature, ram speed is increased right away so the extrudate temperature, heavily influenced by the friction between the billet and the container, increases right away. If the temperature is too high, ram speed is reduced right away.

In this way profile temperature is controlled within a window of +/- 5 degree F. ( +/- 3 degree C.).

Maximum set-point profile temperature must be established by the press operator by a trial and error method, which requires 3 – 5 billets the first time extrusion takes place on a new die.

As a number of dies have a strict upper extrusion speed limit where profile quality problems occur, the system has an individual max. speed setting per die. The press operator must establish this max. speed setting die per die, when the problem occurs. Extrusion speed can not exceed this limit independent of the fact, that max. set-point extrusion temperature has not been reached.
Set-point extrusion temperature and max. extrusion speed plus additional customer specific die related process parameters are kept in a die database. This die database serves as input for the next order. For quality control purposes an additional database, logging relevant extrusion parameters billet by billet including maximum actual extrusion temperature, is incorporated in the system.

**advantages:**

1) productivity improvements in the range of 10% can be expected 
2) recovery will improve with 2 – 3% 
3) dimensions will improve, the alloy will be harder and the profile will be more uniform in quality 
4) the die load will not exceed the die load obtained during normal break through 
5) the system will compensate for major changes in billet temperature, press out of thermal equilibrium and the actual condition of the die 
6) the system can be installed without press down time 
7) pay back time is short 

**shortcomings:**

1) the investment is high 
2) the system does not contain an automatic iterative learning facility to identify set-point extrusion temperature and max. extrusion speed first time a die is extruded 

**PRACTICAL RESULTS WITH CLOSED-LOOP ISOTHERMAL EXTRUSION**

The OPTALEX system from Alu – Mac A/S in Denmark is a closed-loop isothermal control system, which was introduced to the marketplace in 1995.

The first installation in the USA was in fall 1997 at the Wells Aluminum Corp. plant in Belton, S.C. on a 2500 ton - 8” press.

Subsequently another 4 systems have been installed by Wells Aluminum Corp. in North Liberty, IN, Kalamazoo, MI, Belton, S.C. and Monett, MO.

Three of the five systems have been installed at presses, where the installation of the system was the only change made to the press.

On these three presses the following productivity improvements have been obtained:

<table>
<thead>
<tr>
<th>Press # 1: 2250 ton - 8”</th>
<th>Overall improvement on all alloys: 11%</th>
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</thead>
<tbody>
<tr>
<td>6061: 3%</td>
<td></td>
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<td>6063: 10%</td>
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<tr>
<td>6105: 13%</td>
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<tr>
<td>Calculations include all orders.</td>
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</table>

<table>
<thead>
<tr>
<th>Press # 2: 2500 ton - 8”</th>
<th>Overall improvement on all alloys: 12%</th>
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</thead>
<tbody>
<tr>
<td>6061: 11%</td>
<td></td>
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<tr>
<td>6063: 14%</td>
<td></td>
</tr>
<tr>
<td>6105: 13%</td>
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<tr>
<td>Calculations include all orders.</td>
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<th>Press # 3: 1675 ton - 7”</th>
<th>Overall improvement on all alloys: 7%</th>
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<tr>
<td>No break down per alloy.</td>
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<td>Calculations include all orders.</td>
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In general terms Wells Aluminum Corp. has obtained the following additional advantages with the OPTALEX systems:

1) It has been easier to maintain profile tolerances 
2) The hardness of the profiles has improved 
3) All downstream mechanical and metallurgical properties are more predictable and consistent 
4) The setup times are substantially reduced, as the systems “remembers” the optimal press settings 
5) The systems have not caused any die problems 

The following productivity improvements have been obtained on one of the four systems installed by Werner Co.:

<table>
<thead>
<tr>
<th>Press: Clecim 2500 ton - 8”</th>
<th>Overall improvement on all alloys: 12%</th>
</tr>
</thead>
<tbody>
<tr>
<td>6061: 11%</td>
<td></td>
</tr>
<tr>
<td>6063: 12%</td>
<td></td>
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<tr>
<td>6105: 15%</td>
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<td>Calculations include all orders.</td>
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The OPTALEX systems in operation at Wells Aluminum Corp. and Werner Co. are not unique examples. With more that 20 systems in daily operation the general picture is this:
All systems have been able to increase productivity more than 5%. The average productivity improvements are in the range from 8 – 10%, and the scrap reductions are in the range of 2 – 3%. In some cases productivity improvements up to 15% are recorded.

CONCLUSION

A powerful and state of the art press control system is a must to meet tighter production and delivery schedules demanded by the market today.

Innovative technology for isothermal extrusion available in the marketplace today offer the aluminum extruders significantly more pounds from their presses and even higher quality of the profiles.

Major improvements have been achieved regarding infrared camera technology the last few years, and highly reliable and dedicated infrared cameras are available, to measure “profile temperatures”.

When this is combined with years of practical experience with aluminum extrusion and powerful microprocessors able to process sophisticated algorithms the objective to obtain isothermal extrusion has been achieved.

Very few data are commercially available regarding the actual performance of the different isothermal control systems offered to the marketplace today.

The debate regarding accurate measurements of “profile temperatures” will undoubtedly continue for a number of years. But independent of various customers and suppliers points of view regarding this matter, the results obtained by closed-loop isothermal control systems utilizing state of the art infrared cameras and operating in quantities in the marketplace today, prove that a major break through has taken place.

Closed-loop isothermal control systems are available. They work, and it is proven performance.

ACKNOWLEDGEMENTS

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REFERENCES