ABSTRACT—The proportion of dies that are stored with residual aluminum (die prefill rate) has a strong influence on the cost of die shop operations. Prefilled dies require less die shop labor, consume less caustic chemicals, and are not damaged in handling or maintenance. This paper statistically examines the relationships between prefill rate, die failure rate, storage time, and die shop costs in a 4-press soft alloy (6060/6063) plant. Surface finish die failure rate was not increased by storing dies for more than one year, prefilled or not. Prefilled dies gave a slightly higher die failure rate than non-prefilled dies, but the difference was outweighed by the cost savings from using prefill. Other influences on prefill practices are discussed, with emphasis on how to maximize prefill rate without adversely affecting extrusion performance.

INTRODUCTION

When a die finishes a press run, it is either cleaned of aluminum in hot caustic solution, or stored for its next run with aluminum still in place. Caustic cleaning is necessary if the die needs maintenance or inspection. Many plants caustic clean significantly more dies than is required for maintenance and inspection. This increases costs. Control of these costs requires measurement of the proportion of dies that are not caustic processed. This paper discusses this proportion in terms of:

\[
Prefill \ rate (\%) = \frac{\text{number of dies run at press and stored with aluminum}}{\text{total number of dies run at press}} \times 100
\]

If prefill rate is 0%, all dies are caustic processed. If prefill rate is 100%, no dies are caustic processed. Table 1 gives a general outline of the many ways in which prefill rate influences costs, and Figure 1 shows a prefilled die and a caustic-processed die on a storage rack at Capral. The relative size of each cost depends on each plant’s work mix and economic environment (e.g., cost of supplies and labor). Much of the savings are difficult to quantify precisely. Capral uses a rule-of-thumb that an increase in prefill rate from 50% to 75% saves $100K per press per year in chemical and labor costs, plus $100K per year in other costs.
Table 1. Impacts of prefill rate.

<table>
<thead>
<tr>
<th>Chemical costs</th>
<th>Consumption of caustic and disposal of caustic waste. These cost approximately $4(^1) per die in Australia for 8” press dies.</th>
</tr>
</thead>
</table>
| Die handling workload | An increase in prefill rate from 50% to 75% halves the number of dies that are caustic processed, split, cleaned, handled, polished, and assembled. If such an improvement can be achieved, labor cost is reduced.  
A time-motion study was performed at one Capral die shop. Caustic dies each required 27 m of die travel and 34 min of operator time (including die correction). Prefilled dies required 6 m of die travel and 6 min of operator time. |
| Risk of operator injury | Most die shops do some manual die lifting, which can cause back and other injuries. Fewer dies being processed reduces this risk. |
| Risk of die damage | If fewer dies are handled, there is less change of damage to bearings (e.g. impact of flat-faced dies or mandrels on other dies). This damage is almost always repairable, but can result is reduced die life. |
| Risk of die contamination | Dies stored in racks for long periods without aluminum are at risk of contamination from airborne dust. This can be overcome with protective tape. |
| Die correction workload and outcomes | Low prefill rate generally means more work for die correctors. Processing of dies that could have been prefilled is unproductive. It reduces the time available to spend on problem dies and die performance improvement (e.g. collaboration with die designers), which can strongly influence plant performance. |
| Risk of over-polishing | Over-polishing leads to angled or crowned bearings, more die failures and reduced die life\(^{[1,2]}\). Also, die apertures are increased, which results in higher mass per meter and higher production costs if product is sold per length at nominal weight. If dies are not unnecessarily caustic processed, there are fewer opportunities for over-polishing. |
| Recovery | The metal that is dissolved in caustic reduces plant recovery. Even if feeder (baff) ring aluminum is removed (sheared or sawed) for recycling before caustic processing, it still represents a recovery loss through the extra billet length needed to start the die next run.  
For 50 mm thick feeder rings on an 8” press, this loss is about 3.7 kg per die. For 60 die changes per day, 40 t per day, a prefill rate increase from 50% to 75% corresponds to a recovery increase of 0.14%. |
| Die availability | Prefill dies are immediately available for their next production run. Caustic dies are typically unavailable for 12-24 hours. If product is unexpectedly scrapped (e.g. for dents) so that a press order is not competed, a prefill die is more likely to be re-run in time to meet customer delivery date requirements. Also, a higher prefill rate reduces the impact of maintenance problems with the caustic tanks. |

\(^{1}\) One USD is approximately equal to one AUD.
EFFECT OF PREFILL RATE AND STORAGE TIME ON SURFACE FINISH

Background

This section relates to Capral’s Bremer Park, Brisbane plant, where a project is underway to increase prefill rate. Bremer Park is a four press operation, with two 7” and two 8” presses. It primarily runs 6060/6063 alloy, with a small 6106 component.

Dies are stored in an automated storage unit that is well separated from gross sources of moisture and dust. Neither protective tape nor corrosion inhibitors are used to protect dies in storage. The climate is subtropical, with high humidity. Dies are cleaned with an iron shot blaster after caustic processing, and then either hand-polished or extrude honed. Feeder ring aluminum is sawed off before caustic processing.

At the start of the project, Bremer Park’s overall prefill rate was 55%, compared with other Capral plants that are over 80%. Over half of the dies that were caustic processed were designated as “no-prefill”. This requires that these dies be caustic processed every run.

The frequent use of this designation was mainly driven by a belief that prefilled dies give more surface finish problems, especially after they have been stored for more than 6-12 months. This belief appeared credible because it was consistent with the literature\[3\] and with informal discussions with international extrusion companies. However, the project team decided to challenge this belief because of its strong influence on prefill rate.

Analysis

All production runs over a recent 24 month period were analyzed. Surface finish performance was gauged by the number of runs for which press operators coded Rough surface into the production system.
This designation is used for die lines and pickup. It is used both for runs that fail (order is incomplete) for surface finish, and runs that complete their order with just-acceptable surface finish. About half of the Rough surface runs are failures. As with all operator-input data, there are occasional inconsistencies in when Rough surface is input, but the data is thought to be sufficient for current purposes.

Table 2 summarizes the results of the analysis. The prefill rate was 58% over the 24 month period. Some 5.4% of runs using prefilled dies were coded as Rough surface, both for dies stored less than one year and more than one year. Therefore, there was no storage time effect on surface finish for prefilled dies. Similarly, the low 4.4% figure for non-prefilled dies that were stored for more than one year is a good sign that oxidation and contamination in storage are not major problems at this plant.

Table 2. Analysis of die runs in 24 month period.

<table>
<thead>
<tr>
<th>Storage time</th>
<th>&lt; 1 year</th>
<th>&gt; 1 year</th>
<th>TOTAL</th>
<th>&lt; 1 year</th>
<th>&gt;1 year</th>
</tr>
</thead>
<tbody>
<tr>
<td>Prefilled</td>
<td>37607</td>
<td>902</td>
<td>38509 (58%)</td>
<td>5.4</td>
<td>5.4</td>
</tr>
<tr>
<td>Non-prefilled</td>
<td>26952</td>
<td>705</td>
<td>27657 (42%)</td>
<td>6.2</td>
<td>4.4</td>
</tr>
<tr>
<td>TOTAL</td>
<td>66166 (100%)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

For runs using non-prefilled dies, 6.2% of dies stored less than one year were coded as Rough surface, compared with 4.4% for dies stored more than one year. The most likely reason for the higher 6.2% figure is that it would include a higher proportion of dies that had repeated rough surface problems. This can be caused by section difficulty, unusual customer requirements, or a need to produce an order on a badly worn die. Such dies require multiple corrections and therefore give many non-prefilled production runs with short storage time.

It would be very complex to statistically separate this biasing effect of repeat failures. Instead, it is reasonable to conclude that if the repeat failures were removed, the non-prefilled < 1 year value would fall to a figure no less than the > 1 year figure of 4.4%. If it fell to 4.4%, we would have a simple result that non-prefilled runs (4.4%) had 1% less Rough Surface than prefilled dies (5.4%). This corresponds to about 0.5% difference in failed (order incomplete) runs, as about 50% of Rough surface runs are failures.

The main weakness in this analysis is the sample size for the > 1 year data. In the non-prefilled category, only 705 runs occurred in the 24 month analysis period. 4.4% of this is just 31 Rough surface runs. If just 7 additional runs were coded, the total would rise to 38 and the Rough surface % would rise to 5.4%. This is equal to the prefilled Rough surface % and would give a conclusion that there was no effect of prefill on surface finish. Therefore, there is uncertainty in the exact size of the difference between prefilled and non-prefilled data.

It was decided to not consider a sample period of more than 24 months to achieve a larger sample size. This is because die correction and press practices were rapidly changing (improving) at Bremer Park before that time. This would have introduced additional biases into the data. The analysis will be repeated in future years to achieve a larger sample.

The calculated increase in failed runs of 0.5 % represents a cost, which is offset by savings from using prefill. This begs the question of whether there is a net benefit from using prefill. The answer may vary from plant to plant. Consider a example scenario where all of the non-prefilled runs in the analysis were
prefilled, so that there were 0.5% more failed runs on 27,657 runs. This would give 138 additional failures. If these cost $750 each in press and die-shop costs, the total cost increase would be $103,500. However, 27,657 fewer dies would have been processed in caustic at a savings of about $4 per die (chemical costs only). This gives a saving of $110,628. That is, even just the first of the benefits in Table 1 covers the cost of increased die failures. Increasing prefill rate clearly gives a net benefit in this case.

OTHER REASONS FOR CAUSTIC USE

Many factors influence decisions on whether to put a die through caustic after production. Maximizing prefill rate without negative side-effects requires clear understanding of these factors by production and management staff. The following discussion applies to soft-alloy production similar to that described above.

The following situations clearly require caustic processing:

- Die has failed at press and needs maintenance to perform to specification (e.g. shape, surface finish, length variation)
- Die has finished previous run near the limits of specification and would benefit from inspection and possible maintenance
- Die has exceeded predetermined inspection or nitriding intervals. These intervals are either set in kilograms of meters extruded per die cavity. They are ideally set for each die according to past experience of wear rates with similar dies
- New die has run a press trial in un-nitrided condition and nitriding is required after successful trial
- Die is used for production of more than one alloy.

Delicate Dies

One common reason for using caustic is that some dies are considered too delicate to be started prefilled at the press. The concern is that the die would either deform and run off-shape, or possibly break. The concern is typically considered for dies with high-ratio tongues, close tolerances or thin mandrels.

The physical basis for this concern is that the aluminum within a prefilled die is only preheated to the die temperature at the start of the first billet. This temperature is typically lower than the temperature within the die on subsequent billets where the billet temperature, friction and deformation result in a higher temperature. This results in higher flow (and therefore die) stresses during the first billet for prefilled dies.

This traditionally leads to a conservative approach from extrusion and die shop managers, which involves a relatively low prefill rate. Experience in Capal indicates that there is benefit in challenging this approach. The prefill-related benefits outlined in table 1 generally outweigh any small increase in broken or failed dies. Further, if appropriate measures are taken, it is possible to successfully run almost all dies prefilled without increasing the risk of failure or breakage. This requires consistent and good press procedures and temperature control. Some simple measures that can mitigate the higher flow stress on the first billet are:

- Higher die preheat temperature for delicate dies
- Higher billet temperature for first billet
- Lower extrusion speed on first billet.

Hollow dies with thin mandrels that are prone to deflection are often considered to be poor candidates for prefill. Some plants ensure that these dies are not prefilled to minimize the chances of mandrel...
Some extruders employ the opposite theory, that prefill minimizes the chances of mandrel movement. This is based on the observation that the mandrel/s start the run surrounded by, and somewhat restrained from movement by aluminum.

Semi-hollow shutoff dies are often caustic-processed because they are considered delicate. However, these need to be carefully evaluated to determine best practice. The close-tolerance shutoff mating parts dies are often more likely to be broken during disassembly and reassembly (after caustic) than during extrusion. That is, they are safer if they are kept prefilled wherever possible.

**Corrosion During Storage**

Non-prefilled dies will corrode (oxidize, rust) over time, primarily because of moisture in the atmosphere. The rate at which they corrode is influenced by humidity, weather protection, and use of tapes or corrosion inhibitor on the dies. When they corrode too much, they should ideally be cleaned and re-polished before use to minimize surface finish problems. Prefilled dies have excellent corrosion protection. The residual aluminum on the die completely covers the working surfaces, excluding air and moisture so that oxidation cannot occur. Therefore, oxidation during storage is a reason to avoid caustic processing wherever possible.

A number of companies have informally reported that dies that are stored prefilled for more than a certain period (typically 6 or 12 months), are caustic-processed before the next run to avoid surface finish problems. The physical reason for this has not, to our knowledge, been published. We have observed many die bearings where the die was stored prefilled for several years and found no noticeable corrosion. One possible explanation is that the aluminum undergoes metallurgical changes during storage that survive the die preheating process (typically 450°C) and degrades extrusion surface finish. The prefilled die data in table 2 indicates that any such effect was not measurable at Capral - Bremer Park.

**Die Stack Internal Leakage**

Poor control of toolstack tolerances and fits can lead to aluminum leaking past the internal sealing faces and into the gap (typically 0.5 mm) between the die outside diameter, and the die holder inside diameter. This leads to adhered layers of aluminum remaining on die sealing surfaces and outside diameter on prefilled dies.

These layers can cause difficulties when assembling the toolstack for the next run. Most usually, it leads to a large force being required to push the die into the die holder. Most plants have hydraulic equipment to do this when necessary. However, controls are required to limit the applied force because it can be high enough to fracture the die holder.

One potential response to internal leakage is to process leaked dies in caustic. This completely removes the adhered layers and avoids difficulty in tool stack assembly. This approach should be limited to occasional use because of the effect it can have on prefill rate. When leakage occurs, all toolstack components (die, die holder, bolster), should be quarantined and inspected so that the root cause can be identified and remedied. The root cause is usually that either the bolster or die holder is deformed and requires replacement.
REQUIREMENTS FOR SUCCESSFUL USE OF PREFILL

Several controls and systems are required to successfully maximize prefill rate. The most important of these are:

* **Control of die preheat temperature.** Die heating equipment must provide the required die temperatures repeatably and uniformly. An ability to change preheat temperature for individual dies (in single-cell ovens) may help with some delicate dies. Dies need to be brought from preheat ovens to the press as late as possible to avoid cooling.

* **Control of billet temperature.** Billet heating equipment must provide the required billet temperatures repeatably and uniformly. The time between calling the billet and extrusion must be minimized to avoid cooling.

* **Press parameter recipes.** Speed, pressure, billet-start ramp-up profiles, billet temperatures and other press parameters should be standardized for each profile or die. Separate standard settings for the first billet may be required for some delicate dies.

* **Control of non-prefill dies.** If some dies are genuinely found to not perform when prefilled, these dies should be designated as non-prefill. A list of non-prefill dies should be kept and regularly reviewed with a view to trialling and implementing methods (press recipes) to successfully use prefill.

* **Control of inspection and nitriding intervals.** When prefill rate is high, there is a risk that some dies will spend too long between inspection and nitriding events. This can lead to reduced die life if a large amount of die wear occurs before inspection. A system is required where the usage (tonnes or metres) of each die is continually monitored and the die is routed through caustic according to preset inspection and nitriding intervals.

* **Key Performance Indicators (KPIs).** Prefill rate and number of caustic-processed dies should be routinely calculated and displayed in the die shop. This allows early identification of problems and encourages
understanding and ownership from caustic and die shop staff. This is especially powerful when staff understand the impact of prefill rate on their workload, and are empowered to challenge the reasons for individual dies being caustic processed.

Decision-making and feedback. Ideally, caustic and die shop staff would determine which dies are caustic processed. However, die handling and processing times are reduced if the press die operator makes this decision. This is the more usual situation. In this case, die shop staff should provide feedback to press die operators in cases when dies have been inappropriately caustic processed.

Control of die stack leakage. A routine program of die holder and bolster inspection and replacement (or refurbishment) is required to minimize leakage. Inspection should include hardness and dimensional checks. All tools should be inspected yearly. Also, there should be a system where toolstacks that leak severely are quarantined and inspected.

CONCLUSIONS

- Prefill rate is a key determinant of die-related costs, and should be monitored and maximized.
- Analysis of production data indicated that prefilled die runs had about 0.5% higher rough surface failure (order incomplete) rate than non-prefilled die runs. More studies with larger sample size are required to confirm this. However, the cost saving from using prefill would outweigh this failure rate increase for most situations.
- Almost all dies can be prefilled, provided that die preheat and press parameters are sufficiently well controlled. Particular attention is required to control first billet parameters on delicate dies.
- Prefilled dies are less susceptible to corrosion and contamination during storage.
- Poorly maintained die holders and bolsters can lead to undesired caustic use to remove buildup of aluminum on die outer surfaces. Effective tool maintenance systems are therefore required.

ACKNOWLEDGEMENTS

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REFERENCES