Hot forming and quenching pilot process development for low cost and low environmental impact manufacturing.

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Abstract. The Hot Forming and in-tool Quenching (HFQ\textsuperscript{®}) process is a proven technique to enable complex shaped stampings to be manufactured from high strength aluminium. Its widespread uptake for high volume production will be maximised if it is able to wholly amortise the additional investment cost of this process compared to conventional deep drawing techniques. This paper discusses the use of three techniques to guide some of the development decisions taken during upscaling of the HFQ\textsuperscript{®} process. Modelling of Process timing, Cost and Life-cycle impact were found to be effective tools to identify where development budget could be focused in order to be able to manufacture low cost panels of different sizes from many different alloys in a sustainable way. The results confirm that raw material cost, panel trimming, and artificial ageing were some of the highest contributing factors to final component cost. Additionally, heat treatment and lubricant removal stages played a significant role in the overall life-cycle assessment of the final products. These findings confirmed development priorities as novel furnace design, fast artificial ageing and low-cost alloy development.

Keywords: HFQ; Aluminium; Cost; LCA; Process; Simulation

1. Introduction
The GLOBE (Global Legislators Organisation) 2015 international annual legislators’ summit coincided with the 21st meeting of the Conference of Parties (COP21) to the UN framework Convention on Climate Change (UNFCCC). The GLOBE COP21 summit invited legislators, leading members of the judiciary, policymakers, intergovernmental organisations, multilateral organisations, the scientific community, academia, business and the media.

The aim of this formidable assembly was to produce a legally-binding international framework agreement to limit greenhouse gas emissions.

NASA’s Goddard Institute for Space Studies (GISS), which analyses the net climate impacts of emissions from economic sectors, has found that on-road transportation is the greatest net contributor to atmospheric warming now and in the near term (1).
The Nissan Motor Company has stated that over 640M kg of CO₂ can be saved by replacing its internal combustion engine powered (ICE) vehicles with battery electric vehicles (BEV).

The large scale implementation of BEV’s is becoming a reality as a result of better battery technology and measures to increase vehicle range such as weight reduction of the vehicle structure.

Impression Technologies’ HFQ® process originally developed by Imperial College London and The University of Birmingham has the potential to enable complex shaped structural parts to be manufactured from high strength aluminium with little or no elastic recovery (spring-back) after deep drawing (2). This key technology unlocks the implementation of sheet aluminium where only high strength steel could be used previously. Significant weight savings can be achieved if, for example, all of the HSLA parts are to be replaced with high strength aluminium.

In spite of the obvious desire of legislators and policymakers for reduction in greenhouse gasses, new technologies such as HFQ® need to be cost competitive. The LoCoLite FP7 program focused on the industrialisation of the HFQ® technology. A pilot production line (CIPCO) was installed by Impression Technologies Ltd to provide proof of concept, upscaling to high volume production and the supply of low-volume commercial production. The LoCoMaTech H2020 EU program is aimed at lowering the cost of implementing HFQ® aluminium panels for high volume road vehicles.

This paper discusses the approach used to address a common production process development problem; limited development budget for a multi-dimensional process. While all aspects of a process can be improved, it is important to identify the most significant opportunities early in the development process. To this end, simple process models were found to be instructive in highlighting from the possible process improvements those that should be developed to reduce part and in-service costs.

2. The HFQ® Process

![Figure 1: Typical HFQ® Blank Temperature History](image)

Process steps include the ‘Solution Heat Treatment’ (SHT), Forming and in-die Quenching of an aluminium sheet metal blank to produce a shape that has good dimensional accuracy with few or no follow-on forming operations (Figure 1). Further heat treatment steps can be added to achieve precise mechanical properties required for function, depending on the chosen alloy type and application.

Aluminium softens significantly at its solution heat treatment temperature enabling even high strength alloys to be formed into complex shapes with very low levels of elastic recovery consistent with other high temperature forming processes such as super plastic forming.
HFQ® can be adapted to take advantage of the specific characteristics of commercially available aluminium alloys. Target alloys fall into two main categories; alloys that can be strengthened only by work hardening and alloys that can also benefit from artificial ageing to increase their strength.

At room temperature, aluminium alloys differ from steel in that they show a much smaller response to the speed of deformation normally encountered in deep drawing operations. While this is significant for drawing very thin walled cups using alloys such as AA5182-O (3), it has almost no structural effect on panels with a metal thickness above about 0.5mm.

However, above a certain threshold temperature (4) the strain rate sensitivity becomes significant and continues to increase with temperature. The HFQ® process is able to take advantage of the strain rate sensitivity of all of the aluminium alloys to delay the onset of local necking enabling more challenging parts to be manufactured than would be possible at room temperature.

The alloy composition, temperature and rate-dependant work hardening, initial forming temperature and quenching profiles provide a vast array of possible forming parameters that have not previously been available for optimising aluminium deep drawing operations. Each of these parameters has an effect on the final product quality, the cost and on the environment.

The CIPCO production line (Figure 2) is designed to enable process parameters to be investigated for a wide range of automotive panels and aluminium alloys.

3. Process Timing Model (PTM)
Process cycle time is one of the important factors influencing decisions on investment and viability. HFQ® technology is novel to high volume markets like automotive. Many options are available for each element of the production process needed to perform HFQ®, from blank production and management through to final component heat treatment. Solution heat treatment furnace, material handling, tooling design, cleaning and artificial ageing can all be carried out in different ways with different consequences on the final product specifications, energy consumption and cycle time. A simple process timing model was constructed in a Microsoft excel macro to enable identification of the most critical factors impacting the overall cycle time. A schematic of the core process enables identification of the main process steps (Figure 3).

The CIPCO line manufactured by AP&T incorporates many of the best features used in the Hot Press Boron steel process for which its manufacturers have become famous. These include a multi-layer furnace capable of operating with a catalyst or barrier atmosphere according to the needs of the material being heated. The multi-layer design enables up to seven blanks to receive heat treatment at one time. By staggering the loading of the furnace, a constant flow of heated blanks is made available for deep drawing. Loading and unloading of this furnace is governed by the time required to heat the blank to its solution heat treatment temperature.
Some alloys require very close control of the blank temperature. An overshoot of just a few degrees Celsius can cause melting of intermetallic structures which if located at grain boundaries, can severely affect the final mechanical properties. Hence, furnace hold time governs the other process steps in this model.

An optional turntable is added after the MLF to increase process flexibility for special alloys. The PTM macro was used to investigate process sequencing at start-up and during steady state operation. Inputs include timing for each operation and optional and alternative processes such as a turn table. A target number of blanks may be run many times, each with an incremental change to one process variable, such as furnace dwell (alternative furnace technology may be required).

The results show a short SHT furnace duration may not deliver the shortest overall cycle time. Other process steps also need to be shortened. Figure 4 shows a production capability of 29.3 blanks per hour with heat treatment duration of 600 seconds. The PTM identified that it would be possible to increase the capability to 37 blanks per hour if the SHT furnace duration can be reduced to 420 seconds. Any further reduction however, would actually reduce the productivity without other changes to the system, since fewer furnace layers would be able to be loaded in the time available.

![Figure 3 Schematic of Core HFQ® Process](image1)

![Figure 4: Process Timing Model: Sensitivity to Heat Treatment Duration](image2)

![Figure 5: Sensitivity to Heat Treatment Duration and Influence of Pre-Press Turn Table](image3)
The PTM was able to quantify productivity gains using pre-lubricated blanks, an optional pre-press turntable etc. A cost analysis of each option confirmed development priorities to reduce the cost of HFQ®. The addition of a turn table removed the lower limit to heat treatment duration (Figure 5).

Modifications to the SHT furnace, pre-lubrication or no lubrication and a buffer between furnace and press can increase production capacity from 30 to 75 parts per hour for the main HFQ® cell. Research is now focused on reducing the time needed for artificial ageing of 6xxx and 7xxx alloys.

4. Cost Model
A cost model is needed to assess the viability of HFQ® for high volume production. A great deal of data is needed to calculate cost accurately. However, the purpose of this model is to identify, from the main sources of cost, which may contribute the most to cost reduction. The model includes shipping of sheet or coil through to delivery of parts for assembly and scrap back to the metal producer.

Aluminium is the highest cost item, closely followed by the cost of laser trimming. Aluminium can be punched and press trimmed following HFQ®, so this is preferred over laser cutting. Boron steel parts lend themselves more easily to laser cutting than lower cost punching (Figure 6).

![Figure 6: Cost analysis of HFQ® and Hot Pressed Boron Steel "B" Pillar Reinforcement Panel](image)

This example was based on a "B" pillar reinforcement panel for a high volume vehicle using estimates for material prices obtained from part manufacturers and a production rate of 41 parts per hour for HFQ® and 82 parts per hour for hot pressed boron steel. In this example, material (5), punch and trim and artificial ageing offer the main opportunities of cost reduction for HFQ®.

5. Life-cycle Model

5.1. Overview of LCA modelling
Every industrial process or activity implies inputs of materials and energy consumption and, at the same time, generates outputs in terms of solid wastes and emissions released to air and water. Further inputs and outputs are also associated with their use phase and end-of-life. To consider these impacts in detail, there is an imperative need to develop methodologies for the assessment and quantification of environmental burden all along the industrial process life-cycle, in order also to reduce the emissions and waste released and to protect the natural resources. The more restrictive environmental regulations and the ever-increasing awareness from consumers for more environmentally-friendly products, the “traditional” characteristics of costs, performance and quality of products will be more and more linked with their environmental aspects. The ISO 14040 (6) standard states that “LCA studies the environmental aspects of products throughout their life-cycle from raw materials acquisition through production,
use and disposal. The general categories of environmental impacts needing consideration include resource use, human health, and ecological consequences”.

The LCA methodology includes different phases: Goal and Scope Definition, where the main objectives of the study are identified and highlighted along with the Functional Unit (which is the only reference for all the quantities taken into account in the environmental balance); Life-cycle Inventory (LCI): in this step the detailed quantities of energy and material flow (inputs of raw materials and fuels and the outputs of solid, liquid and gaseous wastes) are identified and assessed (all products and by-products are considered); Life-cycle Impact Assessment (LCIA): The Inventory data collected in the previous phase are evaluated, processed and classified into Environmental Impact Categories; Life-cycle Interpretation and Improvement, i.e. the final phase of a LCA study, where the results are considered and possible critical steps in the life-cycle are identified. At this stage, possible alternative processes (e.g. alternative materials and technologies) are identified in an attempt to reduce the product system’s environmental impact.

Among the various impacts categories, in function of the assessment model used, there are: Ozone Layer Depletion, Human toxicity, Fresh water and marine aquatic ecotoxicity, terrestrial ecotoxicity, photochemical oxidation, global warming (CO₂), acidification, abiotic depletion, eutrophication; other methods use the energy equivalents (MJ equivalents).

5.2. Input data needed to assess the HFQ® process

Among the information that needs to be collected for the LCA model, is the type of energy mix used in the country where the product/process is realised, since there might be huge differences among the energy sources used and therefore their final environmental impact. Figure 7 shows the energy mix for the EU-27 countries.

As mentioned for the life-cycle inventory, all data have to be collected about input and output flows of materials, energy, for each of the phases of the production processes. For the HFQ® process, the boundary for the analysis has been considered at the plant doors, including materials from the packaging of the incoming materials, their handling, pre-cutting, forming, post-forming operations and ageing. Shipment is also to be considered for a complete overview (7).

As shown in Figure 8, which gives the characterisation of the HFQ® process for an automotive part, at first sight, the phases with the most relevant impacts are the initial blank preparation phase and the ageing, similar to the result from the cost analysis. This is due to the fact that actually a single relatively small electric oven is used with standard ageing cycles, developed in some cases for aerospace requirements, and therefore interventions in this field might give a positive contribution to the reduction of this consumption. The post forming step has mostly an impact in the negative quadrant, as it includes the recycling of the material which is trimmed off. However, any grade of aluminium can be trimmed and punched in its peak age (highest strength) condition with press tooling which can be much faster and can consume less energy than laser cutting, which is normally the preferred method for trimming hardened boron steel stampings.

Figure 7: EU-27 Energy Mix
Figure 8: Characterisation of an HFQ® formed automotive part - CML 2001 assessment method
A different view of the assessment results show the network diagram with the contributions not only of the various process steps, but also of the aluminium recycling and therefore the reduction of the overall impact (Figure 9)

Figure 9: Network diagram of HFQ® forming: the wider the arrow, the higher to contribution to the impact. The green arrows show the positive impact thanks to recycling, i.e. a gain for the environment.

A direct comparison of HFQ® and boron steel forming (partial input data set) has shown that the manufacturing phase of aluminium has a higher intensity than steel forming (Figure 10)

Figure 10: HFQ® vs Boron Steel forming: cumulative energy method
When considering the whole life-cycle of a vehicle, the lower vehicle mass and end of life recycling delivers much better results (8). Aluminium is unbeatable since the use phase accounts for over 90% of the overall vehicle impact.

6. CONCLUSIONS

6.1. Value of modelling
Risk of upscaling a new process to mass production is linked to the level of understanding of important factors. Process, cost and life-cycle modelling has helped us to focus future research effort. These simple models have also enabled estimation of the value of our development options.

6.2. Recommendations carried forward into development plan
To reduce financial and environmental costs, higher recycled content alloys, reduce duration artificial ageing cycles and alternative SHT strategies should be developed for HFQ.

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BIBLIOGRAPHY

1. Unger N, Bond TC, Wang JS, Koch DM, Menon S, Shindell DT, et al. Attribution of climate forcing to economic sectors. In Proc. Natl. Acad. Sci., 107, 3382-3387, doi:10.1073/pnas.0906548107; 2010.

2. Lin J, Dean TA, Foster AD, Wang L, Blant D, inventors; A method of forming a component of complex shape from aluminium alloy sheet. USA, Europe, Japan, Brazil, Russia, China, Canada, India, Australia, Mexico, South Korea, Malaysia patent GB2473298. 2011 June 14.

3. Picu C, Vincze G, Ozturk F, Gracio JJ, Barlat F, Maniatty AM. Strain rate sensitivity of the commercial aluminum alloy AA5182-O. In Materials Science and Engineering A 390 (2005) 334–343; 2004.

4. Khan AS, Liu H. Variable strain rate sensitivity in an aluminum alloy: Response and constitutive modeling. In International Journal of Plasticity; 2012. p. Volume 36 Pages 1-14.

5. Hall R, Lin J. Low cost materials processing route definition. ; 2014.

6. ISO/TC 207/SC 5. ISO 14040:2006. 2006-07.

7. Herrmann Praturlon A, Hall R. LoCoLite - Environmental impact and life-cycle analysis for HFQ aluminium. ; 2016.

8. Oak Ridge National Laboratories. Life Cycle Assessment - Energy and CO2 Emissions of Aluminum-Intensive Vehicles. ; 2013.