Cost Estimation and the Viability of Metal Foams

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Abstract

Are metal foams *viable*? By viable we mean that the balance between performance and cost is favourable. The answer has three ingredients: a *technical model* of the performance of the material in a given application, a *cost model* giving an estimate of material and process costs, and a *value model* which balances performance against cost. Viability is assessed by constructing a *value function* which includes measures of both performance and cost. It allows ranking of materials by both economic and technical criteria.

At present all metal foams are produced in small quantities using time and labour-intensive methods, and all, relative to the solid metals from which they derive, are expensive. But it is not the present-day cost which is relevant; it is the cost which would be obtained were the process to be scaled and automated to meet the increased demand of one or a portfolio of new applications. The role of a cost model is to assess this, to identify cost drivers, to examine the ultimate limits to cost reduction, and to guide process development.

Here we describe progress in constructing and using cost models for two of the processes by which metal foams are made, and describe our method for assessing the viability of a new material.

1. Technical Cost Modelling

Arriving at a point cost estimate for a component produced by a novel process or material is important but can be accomplished by a simple model or calculation. Greater predictive power can be obtained by introducing elements of *technical cost modelling* (Field and de Neufville, 1988; Clark et al 1997) which exploit the understanding of the way in which the control-variables of the process influence production-rate and product properties. It uses, too, information on the way the capital cost of equipment and tooling scale with output volume. These and other dependencies can be captured in theoretical and empirical formulae or look-up tables which are built into the cost model, giving greater resolution. In addition, informed sensitivity-analysis and scenario-building are enabled through the capturing of the linkages between the technical limitations of the process, intermediate variables such as cycle time, and cost line items.

A schematic of the structure of a technical cost model (TCM) is shown in Figure 1. Each of the empty boxes in this figure represent the calculation of intermediate variables that capture the technical limitations of the process under varying input product specifications, process choices, and selected production volumes. The final output consists of both a range of unit cost numbers and the identification of cost drivers. We have constructed technical cost models for two established processes for making metal foams. They are described briefly in the next sections.

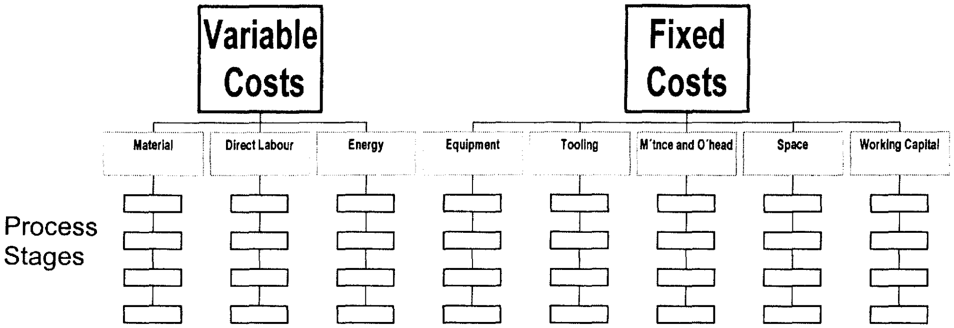

Figure 1: Schematic of a Technical Cost Model (TCM)

1.1 Liquid-state foaming of aluminium

Consider a cost model for the production of panels of a SiC-stabilised aluminium-based metallic foam by the following 4-step process:

a) melting of the pre-mixed alloy
b) holding, providing a reservoir
c) foaming, using compressed gas and a bank of rotating blades
d) delivery of a continuous sheet of foam or of cut panels, via a moving belt

The output of one step forms the input to the next, so the steps must match, dictating the size of the equipment or the number of parallel lines in each step. Data characterising the dependence of desired material density and of production rate on the gas flow rate and the stirring rate has been incorporated in the model and links into the intermediate variables of limiting production rate (LPR, in kg/hour), utilised hours per year (U.hrs/yr), man-hours per year (M.hrs/yr), fraction of capacity utilised (F_c), and number of parallel lines of equipment (PL), which are calculated in the model as shown below:

$$\text{U.hrs/yr} = \text{Hrs/day} \times \text{days/yr} \times F_c \tag{1}$$

$$\text{M.hrs/yr} = \text{Number of staff per line} \times \text{Hrs/day} \times \text{days/yr} \times F_c \tag{2}$$

$$F_c = \text{Production Volume (PV)} \;/\; \text{Line Capacity (kg/yr)} \tag{3}$$

where Line Capacity = Hrs/day x days/yr x limiting rate (kg/hr) x (1-scrap) x (1-downtime)
and, Production Volume = required annual output in kg

$$\text{PL} = \text{number of parallel lines} = F_c \text{ rounded up to the nearest whole number} \tag{4}$$

Through these intermediate variables, the influences of scale-up and of varying product requirements effect the cost line items of equipment, direct labour, and power. Fixed costs are treated in the standard economics fashion, through the use of a cost of capital factor (CCF) and by including the opportunity cost of capital (OCC) associated with the working capital. These factors are defined as:

$$\text{CCF} = \frac{(1+r)^{t_c}\ln(1+r)}{(1+r)^{t_c} - 1} \qquad \text{where, } r = \text{interest rate, } t_c = \text{capital write-off time} \tag{5}$$

OCC = the percentage return that could be earned by investing the capital (6)

A range of product, process, and business variables can be overridden by the user, providing flexibility and the potential for extensive scenario and sensitivity analysis.

The outputs of the model (Figures 2 and 3) show the way in which the cost of the material depends on production volume and also identifies cost drivers. Significantly, the model indicates the production volume which would be necessary to reach the plateau level of cost in which, in the best case shown here, the material cost falls to roughly twice that of the input materials.

1.2 Titanium-hydride expansion of aluminium via powder metallurgical processing
In comparison, consider a cost model for the production of panels of an aluminium-based metallic foam by either the batch or quasi-continuous processes for the powder metallurgical (PM) processing of aluminium foam. For the batch process, there are six steps:

a) Mixing of the Al powder with the powdered foaming agent (< 1% TiH)
b) Cold Isostatic Compression of the powder into an intermediate billet
c) Sintering of the billet (optional)
d) Extrusion of the foamable precursor
e) Placement of Precursor in Mould
f) Batch Foaming of Precursor in Mould

For higher production volumes, automation of steps b, c, and d and of steps e and f have been proposed as follows:

a) Mixing of the Al powder with the powdered foaming agent (< 1% TiH_2)
b) Conversion of powder into precursor strip using the CONFORM process
c) Quasi-continuous foaming of precursor in the mould, meaning that the moulds on a continuous belt are filled robotically, passed through the furnace, opened and emptied.

The rate-limiting step for the current low production volume process is the batch foaming step. The cycle time of this step is heat-transfer limited. The time required to heat the mould then increases with increased part dimensions and the time required to transfer heat into the precursor strips increases both with increasing part dimensions and with part curvature, according to the equation below:

$$t = \frac{\beta \frac{C_p \rho x}{h} \ln\left(\frac{T_3 - T_1}{T_3 - T_2}\right) + \text{Removal and Reload Time}}{\text{Number of Parts in Furnace}} \quad (7)$$

where, t is the cycle time, in seconds, of one unit in the batch foaming stage, C_p is the specific heat of the material, ρ is its density, h is the heat transfer coefficient of the material, x is the characteristic dimension for heat diffusion, T_1 is the initial mould temperature, T_2 is the desired foaming temperature, T_3 is the temperature of the foaming furnace, and β is the adjustment factor for the air gaps left between the precursor strips and the mould surface in curved parts. Values of β are obtained from the known foaming times for moulds of known dimensions. From empirical data, curved parts have an approximately 50% longer foaming time than flat parts because of poor contact and heat transfer between the bars of precursor and the mould surface. The adjustment factor, β, corrects for this. To ensure the validity of assuming heat-transfer, rather than conduction, is limiting, a check of the Biot number is performed, as follows:

$$\text{Biot Number} = \frac{\lambda}{h\,x} \tag{8}$$

If the Biot Number is greater than 1, the heat transfer condition is met.

An important cost driver in this process is the substantial amount of scrap generated in the foaming stage in order to ensure mould filling, shape definition, and to avoid weak zones along the interfaces of the precursor strips where they meet during foaming. Throughout the model, the percentage of material that is lost during the foaming stage is referred to as FOAM_SCRAP and the cost of processing this waste material is reflected in the material cost line item of the batch foaming and continuous foaming stages. As the material can be sold as prompt scrap, the additional material cost in the foaming stage can be expressed as:

(powder cost – price of prompt scrap + cost of processing powder) * FOAM_SCRAP (9)

Accounting for this scrap and the desired relative density of the final part, the amount of precursor material required per part in the foaming stage is:

$$\mathbf{m} = \frac{\text{Desired Relative Density} * \text{Volume of Part}}{(1 - \text{FOAM\_SCRAP})} \tag{10}$$

By running comparison scenarios with this model, it was determined that the CONFORM process is not a viable alternative to the manual steps of billet pressing, billet heating, and extrusion of the precursor strips. After determining the range of equipment capital costs and corresponding production rates of the available CONFORM equipment and inputting these costs and rates into the TCM, the automated precursor production was found to be more expensive than the manual process. This result was unexpected, but arose because the feasible production rates of the CONFORM equipment were limited by adiabatic heating: it is necessary to keep the aluminium powder below the foaming temperature as the powder is being extruded into precursor strips. These low production rates led to the need for parallel lines of expensive equipment.

However, a quasi-continuous foaming process to automate the current rate limiting batch process appears viable from this analysis. As the capital cost associated with this concept production step is unknown, a range of costs were assumed and compared with the manual process. In this way, it was determined that at a production rate of 100 units/hour and a capital cost of $1.5 million, the quasi-continuous becomes cheaper than the batch foaming process at production volumes greater than 70,000 parts per year.

A comparison was run for a simple flat panel of aluminium foam made by the three options of liquid state processing, batch powder metallurgical processing, and the proposed quasi-continuous powder metallurgical process without the uneconomical CONFORM step. This simple flat panel comparison inherently favours the liquid state process of Section 1.1, which is set up for the continuous production of flat panels. Figure 2 depicts the relative cost per unit of each of the different options over a range of annual production volumes. For annual production volumes of up to 20,000 parts, the batch powder metallurgical process is the most economical option. From examining Figure 3, which shows a snapshot of the line item costs for each process at 20,000 parts per year, we can see that it is fixed costs, in particular equipment costs, that drive the low volume cost of both continuous PM processing and liquid state processing higher than that of batch PM processing.

In comparison, Figure 3 also shows the cost drivers for all processes at a production volume of 300,000 parts per year, where the continuous PM process is more economical than the batch PM process. The continuous process reduces the variable costs of direct labour, and avoids the need for multiple parallel lines of batch furnaces at higher annual production volumes. The equipment cost is still large for the quasi-continuous PM process, even after amortisation over significant production volume; however, the direct labour savings now compensate for the higher equipment costs, making quasi-continuous PM processing more economical that batch PM processing. From this analysis and from using the TCM on other proposed products, maximum viable levels of capital equipment expenditure and expected cycle time for a continuous process can be set. The required cycle time, the part size, and the foaming time feed into the calculation of the length of furnace required which, in turn, feeds into the capital expenditure estimate. In this way, the TCM can be used to aid the decision about the suitability of converting to a continuous process.

2. Viability

2.1 Value Functions

The viability of a foam in a given application depends on the balance between its performance and its cost. There are three steps in evaluating it (Figure 4).

The first is the technical assessment (Figure 4, upper circle). Performance metrics, P_i, are identified and evaluated for the foam and for competing materials or systems. A performance metric is a measure of the performance offered by the material in a particular application. In *minimum weight design* the performance metric is the mass: the lightest material which meets the specifications on stiffness, strength etc. is the one with the greatest performance. In *design for energy-mitigation*, in which it is desired that a protective packaging should crush, absorbing a specified energy, and occupy as little volume as possible, the performance metric is the volume. In *design to minimise heat loss*, the metric could be the heat flux per unit area of structure. In *design for the environment*, the metric is a measure of the environmental load associated with the manufacture, use and disposal of the material.

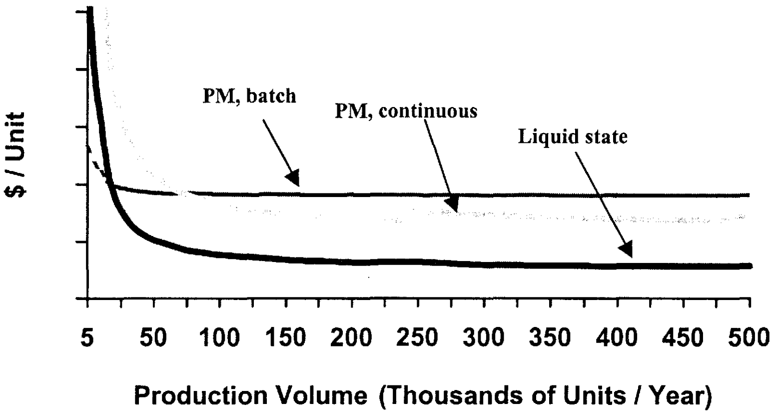

Figure 2: Manufacturing Cost for Varying Production Volumes: Processing of Aluminium Foam by Three Methods

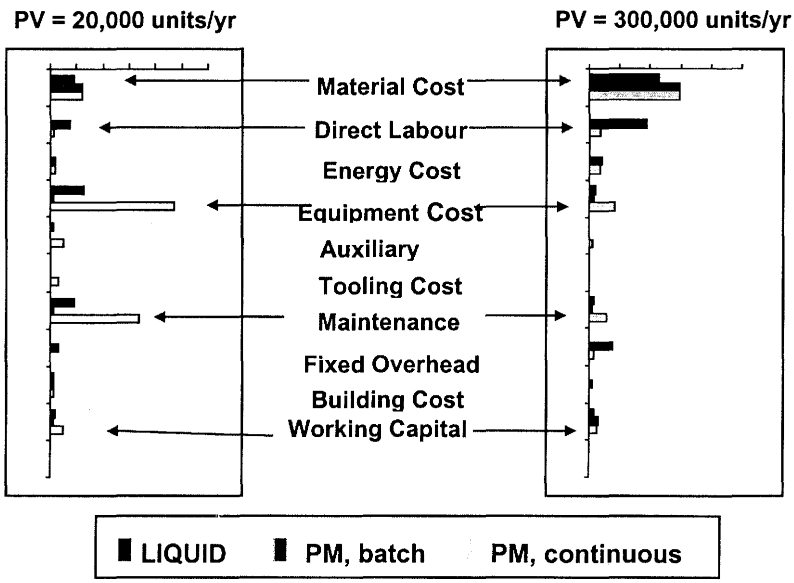

Figure 3: Line Item Cost for Crossover Annual Production Volume of 20,000 and 70,000 units: Processing of Aluminium Foam by Three Methods

The second step is the analysis of cost (Figure 4, lower-left circle): how much does it cost to achieve a part/component with a given performance metric? The quantity of foam required to meet constraints on stiffness, on strength, on energy absorption etc is calculated from straightforward technical models. The cost C of producing this quantity of material in the desired shape is the output of the cost model, as described in Section 2.

The final step is that of assessing value (Figure 10, lower-right circle). To do this we form a *value function*

$$V = \alpha_1 P_1 + \alpha_2 P_2 + \dots\dots\dots - C \quad (11)$$

where the α's are *exchange constants:* they relate the performance metrics P_1, P_2 ... to value, V, measured in $.

For substitution to occur, the difference in value ΔV needs to be large enough to justify the investment in new technology, and there must be sufficient financial or strategic incentive for one or more companies to invest in the new technology, and also, if necessary, in the manufacturing facilities.

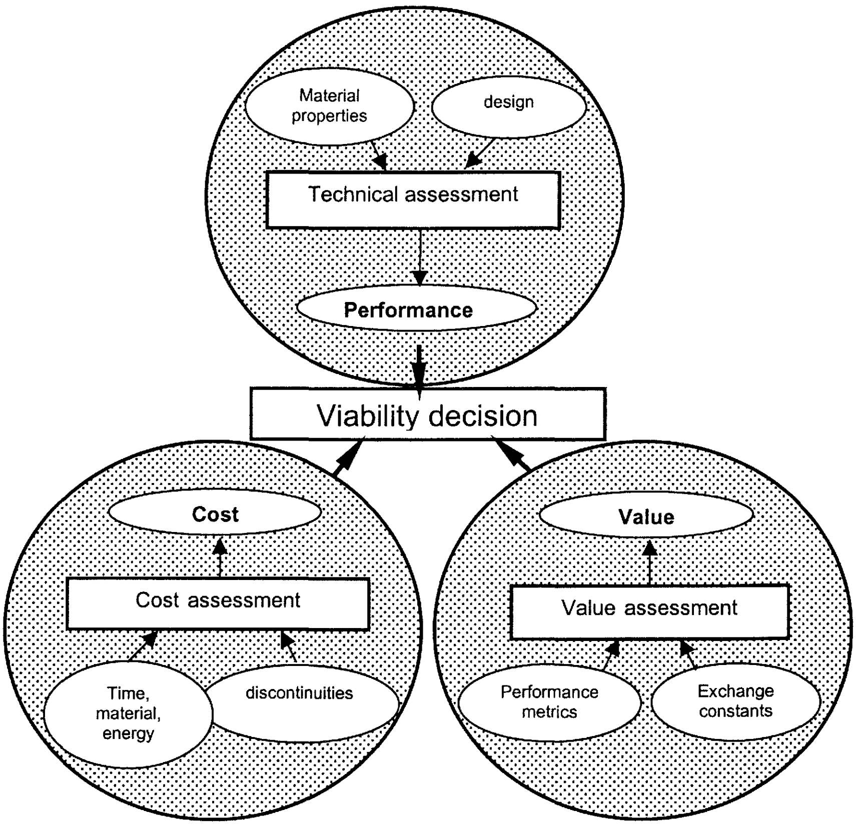

Figure 4: The three parts of a viability study

2.2 The Exchange Constants, α

An exchange constant is a measure of the value of performance. Its magnitude and sign depend on the application. Thus the value of weight-saving in a family car is small, though significant: in aerospace it is much larger. The utility of heat transfer in a heat exchanger is positive; in applications requiring thermal insulation it is negative. The value of performance can be cost-based, meaning that it measures an actual saving of cost, energy, materials, time or information. But value can, sometimes, be perceived, meaning that the consumer, influenced by forces such as scarcity, or advertising, or fashion, or aesthetics, or convenience etc. will pay more than the cost-based value of these metrics.

In many engineering applications the exchange constants can be derived approximately from technical models. Thus the value of weight-saving in transport systems is derived from the fuel saving or the increased payload which this allows. The value of heat transfer can be derived from the price of the energy transmitted or conserved by unit change in this metric. Approximate exchange constants can sometimes be derived from historical pricing-data; thus the value of weight-saving in a bicycle can be approximated by plotting the price P of bikes against their mass m, using the slope (dP/dm) as an estimate of α. Finally, exchange constants can be determined through interviewing techniques (Field and de Neufville, 1988) which elicit the value to the consumer of a change in one performance metric, all others held constant.

3. Conclusions

Cost estimation is an important part of a material development strategy. A new material is viable in an application only if its value, so used, exceeds that of competing materials. Value is a function of both performance and cost and of one or more exchange constants which measure the utility of performance. The value function which combines these allows optimised selection of material and – with a cost model in place – of process to meet a given design specification.

Acknowledgements

We wish to acknowledge the support of the Körber Foundation, the Cambridge Canadian Trust and of the UK EPSRC through the Engineering Design Centre at Cambridge, and of Granta Design, Cambridge, who developed the software illustrated in this article.

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