Novel Energy Reduction and Capital Optimisation for Rotomoulding

NERCOR

DTI Project No. 3530

Techno-economic and Process Models

Report 2

1 Introduction

The accepted project proposal (dated 21 February 2007) envisages possible changes to the rotomoulding process designed to increase the rate of heat transfer to and from the mould. This report shows the effect on cost and on energy of two of these changes.

As detailed below, the overall price of a product ex factory depends on at least 12 variables as detailed in equation (1). Generally, throughput Q is the biggest single factor in reducing unit cost and increasing margin. Assuming that all product can be sold, increases in Q will be inversely proportional to cycle time (t_c). The heating time (t_h) part of t_c is inversely proportional to heat transfer coefficient h from the oven to the mould. Increasing h is thus one major element of the techno-economics of the rotomoulding process.

The overall energy and capital efficiencies of the rotomoulding process are very low by plastics industry standards. This is due to:

- Much of the equipment is idle for 60% of the production cycle, particularly if only one or two moulds are loaded on the carousel.
- Much of the energy supplied is used to reheat the mould and its carousel arm, since these have to be cooled down for safe handling at the end of the cycle.
- Unless 3 or 4 moulds are loaded on a carousel/oven combination, the oven itself will cool during a cycle, leading to more reheating, which will also prolong the heating time (t_h).

For these reasons the project has examined an alternative process (CHARM – see below) where the thermal load is much reduced by eliminating the oven and its associated pipework for recirculating hot air to the oven.

2 Starting Point: Overall Manufactured Cost Equation

The cost (c) of a unit of product is given(Ref 1) by

$$c = (r - s)/\eta + s + u/\eta + (L + f + \beta C)/Q \qquad (1)$$

where

r = raw materials cost per unit made (£)

s = scrap credit for rejected artefacts per unit (£)

η = conversion efficiency = units accepted for sale ÷ units made

u = utilities cost per unit made (£)

L = fixed labour cost associated with plant (£ per annum)

f = fixed overheads associated with plant (£ per annum)

β = $i + m + d$ (yr^{-1})

i = return on capital required (yr^{-1}) – this includes a profit element over and above the loan interest charged on any borrowing (e.g. to pay dividends to shareholders).

m = maintenance cost of capital (yr^{-1})

d = depreciation (replacement or repayment) allowance for capital (yr^{-1})

C = original cost of equipment and buildings associated with a machine (£)

Q = annual output of units accepted for sale (yr^{-1})

2.1 Raw Material Cost per unit made (r)

$$r = \rho V(1 + e)c_m \tag{2}$$

where ρ = mean density of material as made $\left(kg/m^3\right)$

V = Volume of artefact (m^3)

e = fraction of material used which is (edge) trim or similar

c_m = cost of purchased raw materials (£/kg) (includes additives, e.g. pigments)

2.2 Utilities Cost per unit made (u)

$$u = (Ee_i + Gg_i + Hh_i + Ww_i)/Q \tag{3}$$

where E, G, H, W are annual usages of electricity, gas, water and waste disposal services respectively and ei, gi, hi, wi are their respective unit costs.

2.3 Fixed Costs

These are represented by the term $(L + f + \beta C)/Q$ in equation (1).

- Labour costs (L) include an allowance for overtime (if worked).

- Fixed overheads (f) include an element for management, rent and insurance of premises associated with the process.

- βC (β -as defined in the table on page 2) is the annual cost of the equipment (c) associated with the process including all ducting, ventilation and any waste disposal equipment owned by the company and used for process waste.

3 Targets for improvement of the RM process

Looking at equation (1) we reduce unit cost (c) by**:**

- increasing first pass conversion (η)
- reducing utilities cost (u)
- increasing units available for sale (Q)

all of which are very obvious to the management of any process. If the market is limiting what can be sold (Q), then only u and η are important.

Where the market is not limiting then increasing Q by reducing cycle time (τ) is a clear strategy subject to not letting first pass conversion η decrease very much. Clearly scrap recovery (equation (1)) will have a vital role in offsetting any decrease in η.

3.1 Sensitivity of c to various changes

This depends on the proportions of the cost (c) represented by each factor in equation (1). Taking averaged figures from HRM and Techni-form, for purposes of illustration only, assume that before changes:

r ~ 25% of c - raw materials cost

s ~ 50% of r - scrap credit

η ~ 90% - increases with length of run for given product

u ~ 10% - utilities cost including gas and electricity

$(L + f + \beta C)/Q$ ~ 65% - depends strongly on Q.

This figure corresponds typically to around 50 tonnes of product per annum per machine.

Then:

an increase in Q by 10%	decreases c by 6%
a 5% improvement in η from 85% to 89%	decreases c by 1.8%
a reduction in utilities cost (u) of 10%	decreases c by 1%.

All of these percentage changes are reasonable ones to aim at as it is likely that the range of individual costs in the rotomoulding industry as a whole is at least as large as this. Given selling prices of 10-12% above cost (c), improvements of 2-3% would be significant additions to profit (i.e. return on capital (i)) and competivity.

3.2 Effect of Heat Transfer Increases

The heating and cooling parts of the moulding cycle are about equal in duration (20 minutes each). Together they make up about two-thirds of the cycle time (t_c), the other third being taken up by mould charging and removal of the moulding. Thus without reduction in the time for these operations, a reduction of x% in both of the heating and cooling parts of the cycle will at most reduce t_c by ⅔x%.

3.2.1 Increasing effective heat transfer area on the outer surface of the mould

Results shown above in section 3 show an overall rise in in-mould temperature of 8-10 ^oC per minute. The oven air temperature displays a time constant rise towards 300 ^oC, of approximately 25-30 minutes (Figs 3.1 to 3.2).

The heating time constant for the mould and contents is defined as

$$\tau_m = \frac{Mc_v}{hA} \qquad (4)$$

where

h is mean effective heat transfer coefficient for the area A(W/m^2 K)

A is effective heat transfer (m^2)

M is mass of mould (M_1) plus polymer (M_2)

c_v is mass-averaged specific heat for M_1 and M_2.

In our experiments the superficial A has been increased by introducing 10-20 mm aluminium spokes normal to the surface (Fig 3.7). Up to a point these will increase A without decreasing h in equation (4), but if placed too close together they will simply increase the boundary layer thickness (ℓ_b) and reduce h proportionately. While it seemed reasonable to aim at a 15-25% increase in A by this means – this was not realised experimentally without a reduction in h, so that the effect on heat transfer was minimal.

3.2.2 Increasing heat transfer coefficient in existing ovens

A turbulent heat transfer coefficient may be expressed as

$$h \approx \rho_a c_a v_t \qquad (5)$$

where

ρ_a is air density (kg/m^3)

c_a air specific heat (kJ/kg K)

v_t is turbulent velocity <u>normal</u> to surface A.

ρ_a, c_a are known and fixed. Turbulent velocity is typically (0.005 → 0.1) times the bulk flow velocity V_b <u>parallel</u> with the surface A.

Flow shaping therefore has its objective increasing V_b. Where the moulds are aluminium and thermal conductivity thus very high, there is no need for V_b to be increased everywhere, but reduction of dead spots is a good place to start. The principal means by which this can be achieved in existing ovens is by shaping the entrance flow to the oven, so that it acts as a jet on the mould end of the carousel arm.

It is reasonable to aim at a doubling of V_b in particular parts of the mould surface as shown in the following calculation.

If the entrance to the oven is designed correctly, a jet is created which will both entrain air from elsewhere in the oven, increasing the temperature uniformity around the mould, AND impinge on the mould.

- For a swept volume of diameter D the mould velocity V_m is approximately $\pi\varpi D$ where ϖ (omega) is rotation speed. For typical values of ϖ and D this gives V_m around 0.5 m/sec. As expected this creates turbulent flow ($Re \approx 10^5$).
- Given the maximum air circulating rate specified for the RM11 machine (20,000 m^3/hr) and the entrance cross-section (0.2 m^2), this gives an entrance velocity of 30m/sec, which will decay to around 50-70% before hitting the mould. This will give a greatly increased local velocity near the mould for around 5-6% of the rotation time, leading overall to an increase in h of around 30-40% depending on the specific mould-carousel fixing arrangements. As explained above, this would lead to a corresponding reduction in the heating time (t_h) and expenditure of heating energy.

4 CHARM (Electric) Process

As explained in WP5 above, energy intensification and efficiency increases in the CHARM process are obtained by fixing heaters directly to the mould surface. This is not a new concept, but the gains are now potentially considerable, given the likely increases in energy costs in the future.

Unlike the oven process, the electric process does not have an oven and carousel arm to heat and reheat, nor pipework to lose heat from during the production cycle. A large proportion of the heat supplied to the heaters is used to heat the mould and polymer.

There are three major sources of loss**:**

- conductive loss to the carousel arm
- radiation loss from the heaters and mould
- convective loss to the surrounding air

As an illustration using the baseline case specified in Table 3.2 (shot weight 6.9 kg), the corresponding mould area of around 0.7 m^2, and 12 500W heaters, rather than 4 200W heaters in the laboratory experiments (Fig 3.41), we find**:**

total heat load per 6.9 kg shot – 8.2 MJ

of which

polymer heat load per 6.9 kg shot – 3.7 MJ

so crude thermal efficiency = $\frac{3.7}{8.2}$ = 45%

This compares with 2.2% for the oven process for the same shot size.

However it should be noted**:**

1) Electricity prices on which CHARM depends are roughly three times gas prices and likely to remain at this sort of ratio.
2) At today's 50 pence per therm gas price, energy accounts for less than 5% of total selling price from the oven process. Nonetheless a reduction of energy costs by up to 80% would add significantly to profit margins.
3) Moreover electrical process economics are much less sensitive to shot size M and throughput Q, than are the oven economics. This opens the way to making speciality short runs at much more competitive prices.

References

1 S F Bush, Scale, Order and Complexity in Polymer Processing, Proc.I.Mech.E (2000), 214 (part E), pp. 217-232.

2 O K Ademosu, D R Blackburn and G Neilson, Temperature Monitoring in Rotational Moulding, Poly. Proc. Soc. 21st Ann. Mtg. Leipzig (2005).