Additional Information - A Typical Process Cost Model

A Process Cost Model for Investment Casting

In this section we present a slightly different approach to cost modeling. There is no single guiding physical model of the operation. The cost evaluation starts with a detailed process flowchart[1] in which each operation is shown in sequence and the cost for the operation is built up by the summation of the time to perform many individual elements of the operation.

The steps for producing jet engine turbine blades from directionally solidified (DS) superalloys are shown in Fig. 1. In the DS process the mold is slowly withdrawn from the furnace, so that the grains grow in a directional manner parallel to the length of the blade. This produces a structure with practically no grain boundaries perpendicular to the direction of bending stress, so that failure from stress rupture becomes less likely.

The casting process used is investment casting,[2] in which a ceramic mold is made by coating a wax pattern of the part. A number of blades can be made at once by assembling them as a "tree." Then the wax is melted and poured out to create the mold cavity. Vacuum melted metal is poured into the hollow tree of blades, and the temperature is carefully controlled to produce directional grain growth. When the blades are removed from the brittle ceramic mold, they must be trimmed, polished, and heat treated.

In this cost model the unit cost is expressed by a modification of Eq. (16.7) in which all overhead costs are lumped into a single factor LOH that is a composite factor of the hourly labor rate plus an overhead rate.

$$C_m = \frac{\mathrm{LOH}}{nm} \sum t + C_m \qquad (1)$$

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[1] C. F. Barth, D. E. Blake, and T. S. Stelson, "Cost Analysis of Advanced Turbine Blade Manufacturing Processes," NASA CR135203, October 1977.

[2] J.A. Schey, *Introduction to Manufacturing Processes,* 3d ed., pp. 224–25, McGraw-Hill, New York, 2000.

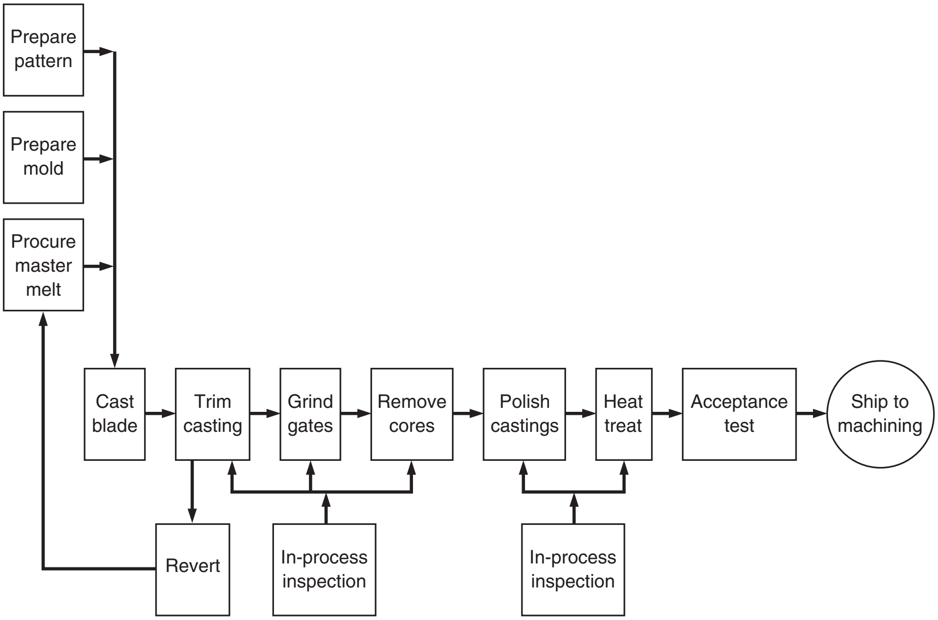

Figure 1
Process flow chart for directionally solidified turbine blades.

C_u = total unit (per piece) cost
C_m = material cost, \$/lb
where n = number of parts per batch
m = number of batches operated simultaneously by one operator
t = time required to complete the operation element for the process

A detailed cost breakdown is prepared for each step in an operation. Here we show the details of the first operation, "prepare the pattern." The pattern is a cluster of wax shapes of turbine blades that will be *invested* in the next step by coating them with a ceramic slurry. The steps involved in producing the cluster are (1) wax patterns containing internal cores are prepared by injection molding (Eq.3), (2) the parts of the pattern are assembled into a cluster of blades (Eq. 2), (3) any defects are smoothed out (dressing the cluster), and (4) the finished cluster is inspected. The cost model for this step in the prepare pattern operation is

$$C_{pp} = \frac{1}{n_{cl}} \mathrm{LOH}\left(t_{amp} + t_{dc} + t_{ci}\right) + C_p + C_{cl} \tag{2}$$

where C_{pp} = cost of pattern preparation
n_{cl} = number of blades per cluster
t_{amp} = time to assemble the patterns in a cluster
t_{dc} = time required to dress the cluster
t_{ci} = time required inspect the cluster
C_p = cost of a wax pattern

$$C_p = \text{LOH}\left(t_{dic} + t_{ip} + t_{ifp}\right) + C_w W_{wp} + C_k \tag{3}$$

where t_{dic} = time to dress and inspect cores
t_{ip} = time required to inject the pattern
t_{ifp} = time required to inspect final pattern
C_w = cost of wax, \$/lb
W_{wp} = wax weight in pattern
C_k = cost of ceramic cores
C_{cl} = cost of components in cluster other than the pattern

$$C_{cl} = \text{LOH}t_{inp} + C_w W_{wmp} \tag{4}$$

where t_{inp} = injection time
W_{wmp} = weight of wax

Clearly this method requires that the costs be established with a high level of detail. An equation similar to Eq. (2) is developed for each process operation shown in Fig. 1. Usually it is just a summation of the time required to carry out an operation in the process step, but occasionally some aspect of the operation can be modeled with a physical model.

The process model for the casting (solidification) step is

$$C_c = \frac{1}{n_c m_f}\text{LOH}\left(t_{ct} + \frac{L}{v}\right) \tag{5}$$

where C_c = unit cost for the casting step
n_c = number of blades per casting
m_f = number of furnaces per operator
t_{ct} = constant time needed to cast a batch regardless of the withdrawal rate
L = withdrawal length
v = withdrawal velocity

Thus, since the withdrawal rate of the casting may be very slow, Eq. (5) shows that this is a significant *cost driver.*

An important aspect in process costs, and especially when the technology is new, is the *process yield*. The simple (uncoupled) yield factor is

$$Y_i = \frac{\text{number of acceptable parts from the } i\text{th operation}}{\text{number of parts that enter the } i\text{th operation}} \tag{6}$$

where Y_i is the yield for the *i*th process operation. For example, the cost of producing one acceptable part from the casting operation is

$$\left(C_c\right) = \frac{C_c}{Y_c} \tag{7}$$

The cost of manufacturing DS blades is shown in the following table in terms of four main cost centers. The table shows which aspect of the manufacturing sequence contributes the most to the product cost. Note the importance of including product yield in the cost analysis. Without considering yield, the coating of the blade for high-temperature oxidation prevention would be the chief cost driver, but when yield is considered, the casting operation is revealed as the high cost contributor because the yield for casting is low.

Percentage Contribution of Cost

Cost center	Without Yield Consideration	Considering Process Yield
Casting	30.2	42.3
Machining and finishing	16.6	24.4
Coating	47.4	25.3
Final acceptance testing	5.8	8.0
	100.0	100.0