

# Chapter 11

## Cold Spray Economics

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### 11.1 Introduction

Cold spray (CS) is employed for scores of applications, from the formation of thin metallic coatings to the production of free-standing shapes. The costs from application to application can vary significantly, but the cost for each is dependent upon the same set of operating parameters. Once defined, these parameters can be used to accurately calculate the cost of a finished product or can be used to predict the cost of a potential product. The methods presented here assume that a complete product has not yet been fabricated, and cost estimates will be based upon the characteristics of the desired product. The methods presented can thus be used to calculate quotation prices for prospective customers, for example, by spray shops.

From an original equipment manufacturer (OEM) perspective, economic affordability of a proposed CS-based manufacturing process is prerequisite even for the release of development budget. In the run-up to a technical deep exploration, future costs need to be estimated largely in absence of knowledge about the final manufacturing process. When CS is considered to replace a prevailing thermal spray process, a simplified cost comparison may be appropriate. Benchmarks against entirely different manufacturing or repair routes like, for example, galvanization, casting, milling, cupping, sintering, extrusion, brazing, welding, or cladding require, however, the estimation of the total CS costs comprising consumables, investment, and labor. Those will have to be estimated reliably, using a minimum of speculative input about the CS application not yet developed.

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Several approaches have been taken in the past to count the costs of CS (Papyrin 2002; Gabel 2004; Karthikeyan 2005; Pattison et al. 2007; Champagne 2007; Helfritch and Trexler 2011), from general considerations to full process simulations as featured in the web-based software by Kinetic Spray Solutions (KSS), Buchholz, Germany (<http://kinetic-spray-solutions.com/>, 2013). These studies have in common that they assume particular cases for the cost modeling, or use more process data than required for actual cost prediction. Therefore, a general analysis of the cost structure of CS is presented in this chapter which is apt to estimate manufacturing costs *from the minimum of input required*. It allows comparison of CS with different manufacturing processes and has proven useful for assessing the economic viability of technically interesting CS application ideas.

## 11.2 Basic Framework

CS accelerates powder particles suspended in a gas. The gas–particle suspension is accelerated by expansion through a supersonic nozzle. The resulting high-velocity particles impact upon a substrate to create a deposition. From this simple description, one can conclude that powder and gas costs and their rates of usage are major contributors to the overall product cost.

Manufacturing costs all reside within three classic categories:

- Materials costs
- Direct labor costs
- Overhead costs

Gas and powder are materials costs. The salaries paid to workers while engaged directly in manufacturing a specific product are direct labor costs. All other costs such as utilities, depreciation, maintenance, etc. are indirect overhead. These costs are interrelated and are subject to task difficulty. In the sections below, we consider each cost category in detail.

### 11.2.1 Materials Costs

Materials costs can be determined based upon the dimensions of the deposited product and the efficiency of deposition. The product will contain a known volume of deposited powder. Assuming negligible porosity and known density, this volume gives the mass of deposit. The mass of powder needed for the product is therefore that of the deposit plus estimated overspray, divided by the fractional deposition efficiency (DE). The DE can be obtained from a trial spray of the powder, can be estimated from similar applications, or can be iteratively calculated. Once the mass of powder is known, the mass of gas needed for powder acceleration can be simply calculated by dividing the powder mass by the ratio of powder to gas, typically 0.05. Given the masses of powder and gas, the costs of these materials are simply

the masses multiplied by the cost per mass, such as dollars per kilogram. In addition, the time needed for a single part fabrication can be calculated from the mass of the gas needed, the gas pressure and temperature, and the nozzle throat diameter. While this time is not needed for material cost calculations, it is needed for labor costs below.

### **11.2.2 Direct Labor**

Labor rates, dollars per man-hour, are known, and the hours needed for product completion are known from the calculation described above. Time must be added to take into account initial planning and setup. This time includes onetime initial fixture assembly, robot programming, and operating parameter determination. If multiple pieces are manufactured, then this onetime cost is shared by piece. While rates may vary among workers, typically an average rate for all workers is assumed. The cost of direct labor as described here assumes that the worker is employed in other activities when not operating the CS system. If the worker is paid a salary regardless his activity, then this labor cost must be part of fixed overhead and must be subjected to utilization considerations, as described below.

### **11.2.3 Overhead**

This cost category can be further divided into two sub categories:

*Variable overhead*, such as utilities for direct production, which changes as production changes

*Fixed overhead*, such as administration, rent, heating and lighting, maintenance, and capital recovery, which remains independent of production

The cost of direct use of electricity for the production of a product by CS can be easily determined. Electricity is used to heat and sometimes to compress the gas used. The usages can be straightforwardly calculated from the temperature, pressure, and flow rate of the gas. Other electrical usages are for robot motion and control systems, but these are negligible in comparison with gas treatment. Once the rate of electricity usage is determined, the total usage in kilowatt-hour can be calculated by multiplying by the production time. The cost is then obtained by multiplying by the purchased cost of electricity in dollars per kilowatt-hour.

Fixed overhead is apportioned to individual jobs depending on the amount of time that particular job requires in relation to all other jobs, and this is where the concept of utilization must be introduced. Utilization is the percentage of time the CS system is used with respect to the total time that is available. Utilization is a measure of how effectively the available resources are being put to use. So the amount of fixed overhead charged to an individual job is equal to (total fixed cost per year/available operating time per year)  $\times$  (total job time/fractional utilization). It will be seen that utilization is a major cost factor.

The capital recovery factor (CRF) method for calculation of depreciation takes into account the declining cost of the equipment, as well as the cost lost to interest payments if the purchase money were used instead as a loan. This is similar to a mortgage payment, which consists of principal and interest. This calculation yields a higher fixed cost than straight-line depreciation, unless interest rates are zero. The yearly depreciation cost, calculated by the CRF method is given by:

$$\text{Yearly depreciation cost} = \text{CRF} \times (\text{capital cost} - \text{salvage cost})$$

$$\text{CRF} = \frac{i(1+i)^n}{(1+i)^n - 1} \quad (11.1)$$

where  $i$  is the fractional interest rate, for example,  $5\% = 0.05$ , and  $n$  is the years of ownership.

Yearly maintenance is generally estimated as a percentage of capital cost, for example,  $5\%$ . Other fixed overhead costs, such as rent and administration are straight-forward, and should be apportioned with respect to fraction of total floor space used and fraction of administrative time devoted to CS.

#### 11.2.4 Combined Costs

The cost determination steps described above are easily assembled and carried out in a spreadsheet program. An example of a typical spreadsheet is shown in Fig. 11.1. Values that must be input, such as gas used and labor rate, are shown in italic. The remaining values such as flow rate and time for completion are calculated by the spreadsheet. The costs by category are then also calculated. A pie chart allows for quick assessment of the importance of various cost drivers. For this spreadsheet, the gas flow is calculated from knowledge of the nozzle throat diameter and the gas conditions upstream of the throat. Time for completion, which is needed for the determination of most cost contributions, is simply calculated by dividing total powder mass used by the powder feed rate. The powder mass needed is affected by the volume of the part, the DE, and the overspray fraction. For example, the time needed to complete a single part is given by

$$\text{Powder mass needed} = \left[ \frac{(\text{part volume})(\text{metal density})}{(\text{fractional DE})} \right] \times \left[ 1 + \text{fractional overspray} \right]$$

$$\text{Time for completion} = \text{powder mass used} / \text{powder feed rate}$$

The electricity needed to produce a part is calculated by adding the usages of the gas heater, the gas compressor, and the exhaust fan and then multiplying by the time needed to complete a part. Electricity usage of the compressor and heater can be calculated from the known flow rate and conventional power equations. The ventilation fan power is assumed to be  $15 \text{ kW}$  for this spreadsheet.

INPUT DATA				CALCULATED VALUES	
nitrogen (0) helium (1)	0			gas flow, NCMH	94.1
throat diameter	2.7	mm		powder to gas, %	4.7
feed rate	5.5	kg/hour		powder per piece, kg	1.77
gas temp after heating	500	degree C		time per piece, hr	0.32
compressed gas pressure	4	MPa		elect per piece, kWhr	11.9
deposit volume	125	cu cm			
number of pieces	100			powder cost	\$17,679
overspray	10	%		gas cost	\$530
material density	9	gm/cc		labor cost	\$4,511
deposition efficiency	70	%		administration	\$6,014
unit powder cost	100	\$/kg		utilities & rent	\$4,010
unit nitrogen cost	0.14	\$/kg		maintenance	\$1,804
unit helium cost	30	\$/kg		depreciation	\$2,015
unit electricity cost	0.15	\$/kWhr		production electricity	\$179
pre-spray set up time	8	hours		Cost per Piece	\$366
set-up time per piece	0.20	hours		Total Job Cost	\$36,562
hourly labor rate	75	\$/hr			
equipment capital cost	900,000	\$			
equipment life	15	years			
salvage cost	300,000	\$			
interest rate	3	%			
system utilization rate	75	%			
maintenance, % of capital	5	%			
yearly administration	150,000	\$			
yearly rent, utilities	100,000	\$			

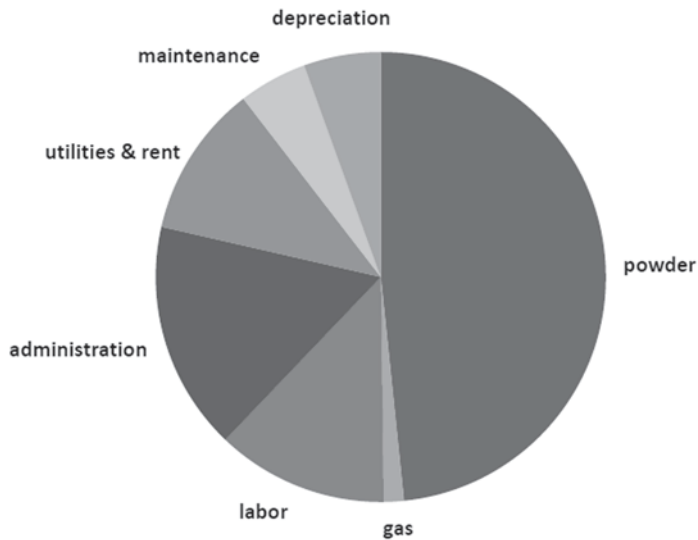


Fig. 11.1 The cost calculation spreadsheet. NCMH normal cubic meter per hour

All of the unit costs, cost rates, and fixed costs of the left-hand column must be the input. The pre-spray setup time is the time needed for tasks which need to be completed before actual spraying, and include items such as powder purchase and robot programming. The setup time per piece is the time it takes to remove a completed piece and install a new base for a subsequent piece. The hourly labor rate

includes only salary and fringe benefits directly paid to the operator. The spreadsheet assumes only one worker for all tasks. Yearly administrative cost is the cost for supervision, sales, clerical, etc. devoted to the operation of the CS system considered. The yearly rent is similarly prorated, for example, where the CS system occupies only part of a building and the other production systems occupy the remainder.

The job costs are then calculated, shown in the lower, center column. Powder and gas costs are based upon amounts used and upon unit costs previously determined. The labor cost is simply the labor rate times the sum of all the time needed to complete the job, including setup. Overhead values for a single job are prorated based upon the fraction of time needed to complete the job divided by the available time per year (here 2000 h), divided by the fractional utilization (U). For example,

$$\text{Prorated admin} = (\text{yearly admin})(\text{total job time}) / 2000(U).$$

## 11.3 Component Effects

Considering Fig. 11.1 to be a base case, we can estimate the relative importance of each parameter by its variation. There are often trade-offs that can be made between parameter values that can reduce costs. For example, a more expensive powder may allow the use of nitrogen instead of helium. The effects of major cost-affecting parameters are examined below. All of the calculations made are based upon a variation of parameters given by Fig. 11.1.

### 11.3.1 Gas

By far the largest influence on final cost is the gas used. This can be inferred from the difference in unit price between nitrogen and helium. Adjusting for higher DE and lower feed rate, when the nitrogen used in Fig. 11.1 is switched to helium, the cost increases from US\$ 36,562 to US\$ 111,329. The cost increase is almost entirely due to the difference in unit costs between nitrogen and helium as can be seen from the comparable cost distributions shown in Fig. 11.2. On first look, it would seem unreasonable to ever use helium; however, there are quality benefits resulting from helium use that are not evident from a manufacturing point of view. Helium can yield improved bond strength and decreased porosity. Nitrogen will sometimes not produce high enough particle velocity needed to allow hard, refractory particles to deposit. System recycle of helium would significantly offset the cost increase described in this example.

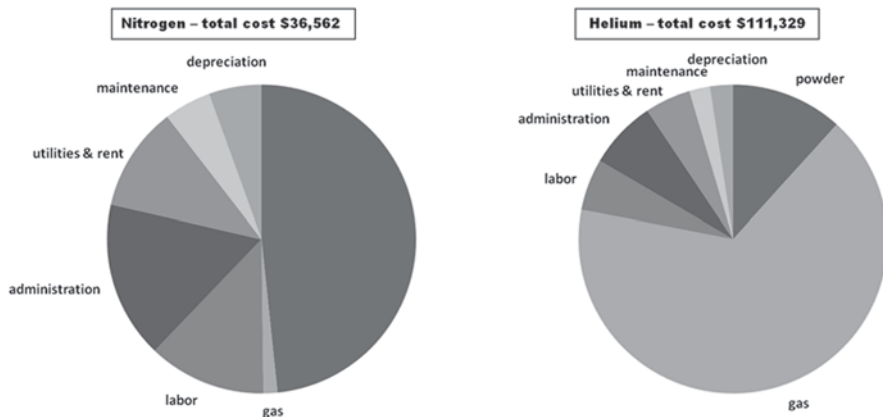


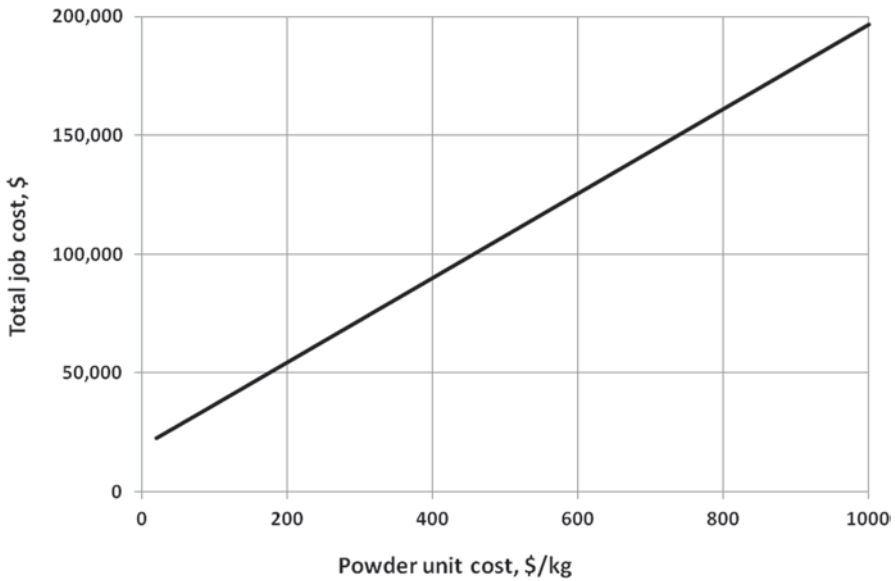
Fig. 11.2 Cost distributions of nitrogen use (left) versus helium use (right)

### 11.3.2 Powder Feed

An often overlooked parameter when attempting to minimize cost is the powder feed rate. This is especially true when operating with helium. Clearly, increasing powder feed rate will shorten the time required for completion, which in turn decreases total gas consumption, labor cost, and prorated overhead. For the example above for helium operation, the US\$ 111,329 cost was based on a feed rate of 2.5 kg/h, which results in a powder flow equal to 5.3% of the gas mass flow. Increasing the feed rate to 5 kg/h, without any other changes, would decrease the cost to US\$ 66,460. The limit to arbitrary increase of powder feed rate is the carrying capacity of the accelerating gas. Gas flow is relatively unaffected when accelerating powder composing 5% by mass of the gas mass flow. Gas and hence particle velocities decrease as powder feed rate exceeds 5%, which in turn adversely affects DE and deposit quality.

### 11.3.3 Powder Cost

While the unit cost for the purchase of gas does not vary significantly from job to job, the cost of powder can vary between US\$ 20/kg and US\$ 1000/kg. The powder costs often contain atomization and/or milling costs, so that the forming process “atomize/mill—consolidate by CS” a priori adds costs to the raw material price. For the case described by Fig. 11.1, the effect of only changing the powder unit cost is shown in Fig. 11.3. The total job cost can change tenfold over the possible range



**Fig. 11.3** The effect of powder cost on overall cost, based on the example of Fig. 11.1

of powder unit costs. This result weighs in favor of shopping for the lowest powder cost, but the qualities of the powder can directly influence the quality of the deposit and the DE of the specific operation. Determination of the deposit quality and DE among powder candidates must be done by means of test CS runs. Once the results from the test runs are known, the DE's and unit costs can be inserted into the cost spreadsheet and job costs determined. A judgment can then be made with respect to the cost–deposit quality trade–off.

### **11.3.4 Deposition Efficiency**

As described above, powder characteristics directly affect DE. For a given alloy, particle shape and particle size distribution are the principal powder determinants of DE. Particle density is also important when other alloys are included. Besides powder characteristics, operating parameters such as gas pressure and temperature have a large influence on DE. For the case described by Fig. 11.1, the effect of DE on job cost is shown in Fig. 11.4. The figure clearly shows the importance of maximizing DE. Powder characteristics and operating parameters can be adjusted to maximize DE. Computer models are sometimes used to predict DE and to determine an optimum set of parameters, but trial CS runs are generally more accurate and preferred.



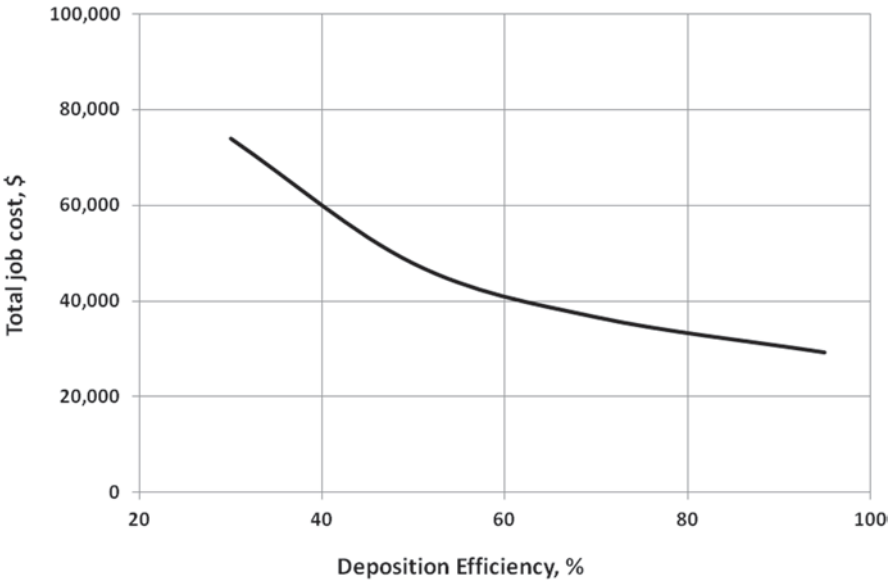


Fig. 11.4 The effect of deposition efficiency

### 11.3.5 Utilization

Labor and prorated overhead costs are strongly dependent on the time needed to complete the job. Clearly, labor rates, depreciation cost, administration yearly cost all directly affect the bottom line job cost, but the actual time that these services are used for the manufacture of the specific job is what assigns their prorated costs to that job. A second factor, related to the job time, is utilization. Utilization is simply the amount of facility time spent in productive utilization, divided by the total time available. Hundred percent utilization means that the system is in full use throughout the year without any idle time. Figure 11.5 shows how utilization affects costs for the case described by Fig. 11.1. A larger portion of fixed overhead costs must be assumed by each job as utilization decreases, and in this case, job costs can almost double as utilization decreases to below 50%.

### 11.3.6 Number of Parts to Be Produced

Given a constant, onetime, setup period (robot programming, purchasing, etc.), the cost per piece obviously decreases as this setup cost is shared with many pieces. Again, considering the case described by Fig. 11.1, the effect of mass production is

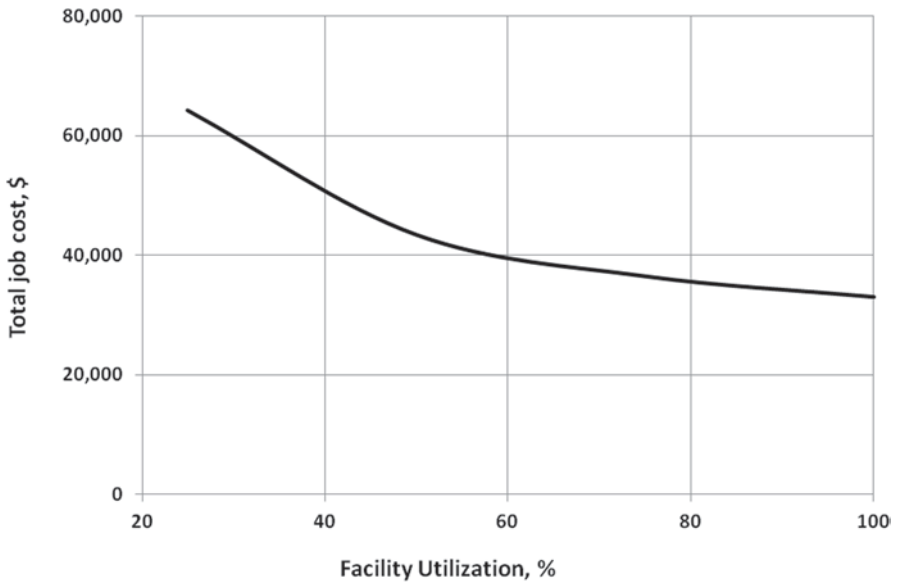


Fig. 11.5. The effect of utilization

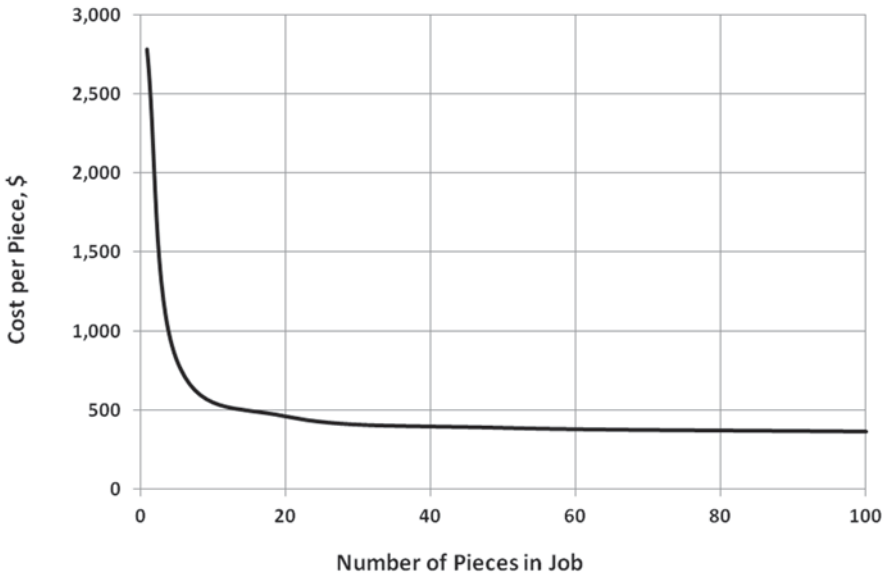


Fig. 11.6. The effect on cost per piece by the number of pieces made

shown in Fig. 11.6. For this example, with 8 h of up-front setup, the cost per piece does not increase significantly until fewer than ten pieces are to be produced. Below ten pieces, the cost per piece increases significantly as up-front costs are shared with fewer pieces.

## 11.4 Determination of Operating Parameters

CS parameters are often adjusted to provide maximum particle velocity and DE, which generally results in optimum deposition characteristics and maximum cost. A cost spreadsheet allows the cold sprayer to balance deposit quality with cost. Until deposition models are improved, the characterization of DE and deposit quality is best done by means of trial spray runs. A matrix of variables may be gas type, pressure, temperature, and feed rate. The DE would be measured for each run. The measurement of deposition quality could include cross-sectional examination, bond strength, tensile strength, etc., depending on the specific characteristics desired. Costs could be calculated for each run and associated DE. Data generated in this way would then yield how the minimum cost for acceptable quality could be achieved.

For industrial applications, the bonding strength of a CS coating to the substrate, the tensile strength of a CS deposit, its porosity or its ductility, etc. are subject to specification. In the language of mathematics, these properties define *constraints* to the feasible CS processes. The specification has to be met while there is little advantage from exceeding it. Therefore, these properties normally do not serve as a *quality function* for an optimization. The optimization of a CS process should be carried out in order to minimize its total costs (is equal to quality function) while obeying the constraints resulting from coating property specifications.

### Decision-Making Example

An example of cost-effectiveness control is as follows. It is desired to coat 20 tubes, 3-cm diameter and 1-m length, with 500  $\mu\text{m}$  of nickel. This yields a coating volume of 24  $\text{cm}^3/\text{tube}$ . The corresponding cost spreadsheet for helium gas is shown in Fig. 11.7. Table 11.1 can be generated, once the deposition efficiencies and porosities are determined from the test runs and the costs are determined from the spreadsheet. Figure 11.8 shows the porosity and cost values of Table 11.1 for the two gases. A desired porosity of 0.2% or under would require helium gas and cost US\$ 400 per unit. If 0.4% porosity were acceptable, then nitrogen could be used, and the cost per unit would be at most US\$ 300 per unit. The costs are seen to increase as porosity increases for both gases, which seems counterintuitive. Although higher pressures and more gas are used to yield lower porosities, the increasing deposition efficiencies result in decreases in powder usages. The decreased cost of powder more than compensates increased gas costs and results in a net cost savings.

## 11.5 Cost Model of CS

The calculations discussed above (and performed by the spreadsheet in Fig. 11.1) can be combined to one neat equation. The derivation of the equation also explains the physics of the CS process. This equation contains fewer parameters than the spreadsheet has input cells, for three reasons:

INPUT DATA				CALCULATED VALUES	
nitrogen (0) helium (1)	1			gas flow, NCMH	249.8
throat diameter	2.7	mm		powder to gas, %	4.9
feed rate	2.2	kg/hour		powder per piece, kg	0.25
gas temp after heating	600	degree C		time per piece, hr	0.11
compressed gas pressure	4	MPa		elect per piece, kWhr	6.3
deposit volume	24	cu cm			
number of pieces	20			powder cost	\$404
overspray	10	%		gas cost	\$3,065
material density	9	gm/cc			
deposition efficiency	94	%		labor cost	\$1,072
unit powder cost	80	\$/kg			
unit nitrogen cost	0.14	\$/kg		administration	\$1,430
unit helium cost	30	\$/kg		utilities & rent	\$953
unit electricity cost	0.15	\$/kWhr		maintenance	\$429
pre-spray set up time	8	hours		depreciation	\$479
set-up time per piece	0.20	hours		production electricity	\$19
hourly labor rate	75	\$/hr			
equipment capital cost	900,000	\$		Cost per Piece	\$392
equipment life	15	years			
salvage cost	300,000	\$		Total Job Cost	\$7,833
interest rate	3	%			
system utilization rate	75	%			
maintenance, % of capital	5	%			
yearly administration	150,000	\$			
yearly rent, utilities	100,000	\$			

Fig. 11.7 Coating a tube with nickel example. NCMH normal cubic meter per hour

Table 11.1 Porosity and cost changes resulting from operational changes

Gas	Pressure (bar)	DE (%)	Porosity (%)	Cost per unit (\$)
He	20	80	0.39	447
He	30	90	0.23	407
He	40	94	0.16	392
N2	20	13	1.08	541
N2	30	24	0.58	339
N2	40	34	0.41	280

DE deposition efficiency

The CS deposit mass on one work piece, as well as the number of pieces, is eliminated by referring to a CS deposit unit mass of 1 kg.

Expenses for setup times are neglected because they are independent of the CS process parameters. They can simply be added after using the equation.

The last nine input parameters of the spreadsheet in Fig. 11.1 effectively reduce to an hourly rate which is used in the equation explicitly.

To calculate the hourly rate, the depreciation period is divided into productive and unproductive hours, as visualized in Fig. 11.9. Mobile spray units gain less productive hours than stationary CS systems in a workshop, due to travel times. On top of depreciation, the plant causes running costs for administration, rent, and maintenance. The

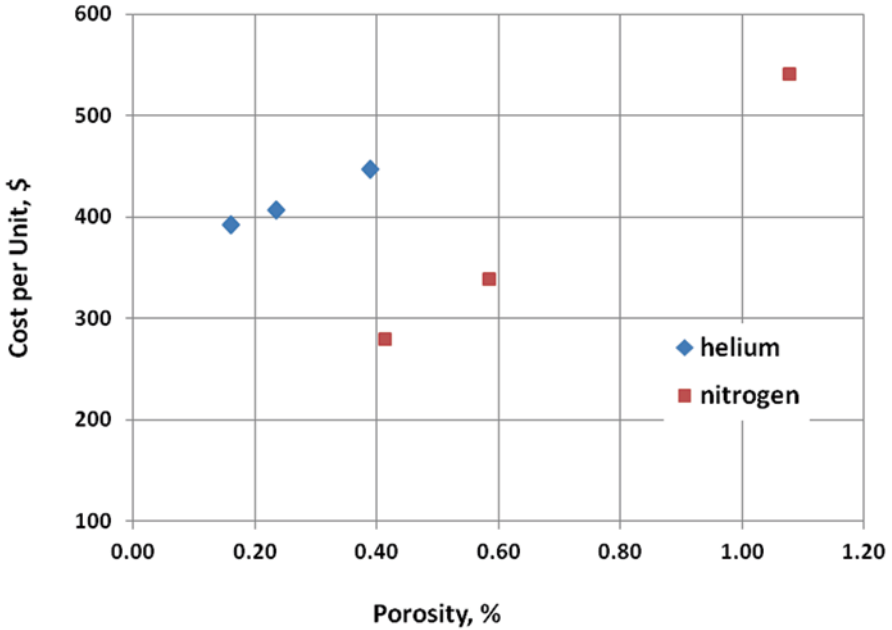


Fig. 11.8 Production cost versus porosity achieved for nitrogen and helium

total of these four costs, divided by the number of productive hours, is an equipment hourly rate adding to the hourly labor rate. The resulting total hourly rate,  $U_{hr}$ , covers all expenses for having the facility available. In the cost calculation module of the KSS software, the two hourly rates for equipment and labor can be set directly. In addition, there is a default calculation of the equipment hourly rate from the depreciation period, capacity utilization, and a variety of investment and rent items plus separate maintenance and repair hourly rates covering predefined system components.

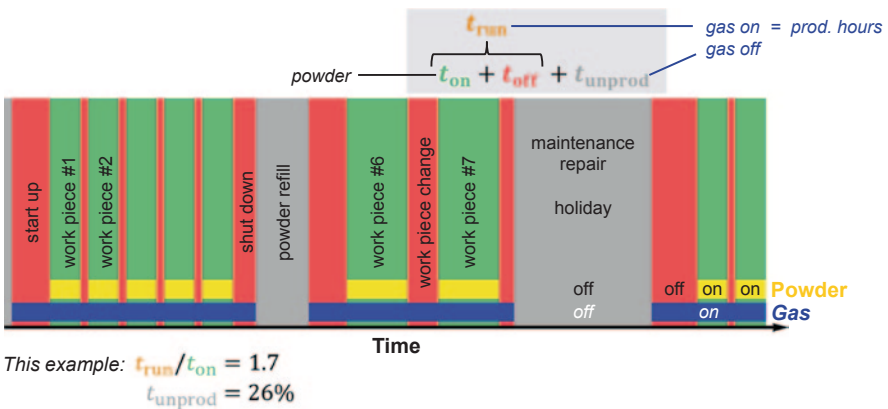


Fig. 11.9 Partitioning of the depreciation period into productive and unproductive hours and visualization of the  $t_{on}$ ,  $t_{off}$ , and  $t_{run}$  times

The costs of process consumables (powders, propellant gas, and electric power) all are accounted for per unit amount of CS deposited material (1 kg), rather than per time unit (1 h). The reference unit 1 kg is convenient for estimating future production costs because the mass of CS deposited material per piece of product is known. The costs of equipment and labor are allotted to the reference unit 1 kg by the time  $t_{\text{run}}$  required for spraying and handling during deposition of that 1 kg material, applying the hourly rate  $U_{\text{hr}}$ . In case the system components are systematically worn out by certain powders (e.g., irreversible clogging or throat erosion of nozzles), the recurrent replacement costs may be allotted to the respective powder price  $U_{\text{pvd}}$  since the damage level correlates with the quantity of powder processed.

### 11.5.1 Generic Cost Function

In this section, a generic expression for the total costs of 1 kg CS deposit,  $C_{\text{tot}}$ , is presented. All model parameters are summarized in Table 11.2, together with their units. Some of them are explained in the following.

Productive hours are defined as the time when the gas flow is on. Thus, breaks for powder refill, maintenance, etc., do not add to the equipment run time but are covered by the hourly rate  $U_{\text{hr}}$ .

It may be advantageous not to shut down the gas flow during a change of work pieces, to avoid the delay associated with gas heater shut down and restart. However, the powder feeder would be stopped during work piece change, to save expensive powder. Hence, the equipment run time required for producing 1 kg of CS deposit,  $t_{\text{run}}$ , is divided into a portion  $t_{\text{on}}$  where powder is fed, and a powder feeder idle portion  $t_{\text{off}}$  where only gas is flowing, see Fig. 11.9:

$$t_{\text{run}} = t_{\text{on}} + t_{\text{off}}. \quad (11.2)$$

At turning points of spray tracks, CS deposits tend to pile up to excess thickness. To avoid this, track turning points are often placed outside the work piece edges which results in an extended spray track length or a virtual augmentation of the work piece surface area. The virtual, relative enlargement of the work piece is expressed by an overspray factor,  $1+GL$ , where GL means “geometric loss.” For example, in the case of constant nozzle motion speed, GL is the ratio of the cumulated spray track lengths out of, and on, the work piece, see Fig. 11.10.

Let  $\dot{m}_{\text{pvd}}$  be the powder feeding rate and  $\dot{m}_{\text{gas}}$  the gas flow rate. Low-pressure gas dynamic spray (LPGDS) systems inject the powder in the expanding section of the Laval nozzle, using atmospheric air at ambient temperature. For LPGDS systems,  $\dot{m}_{\text{gas}}$  refers to the heated main gas flow through the convergent section of the nozzle. The powder-to-gas mass loading ratio is defined as

$$w = \frac{\dot{m}_{\text{pvd}}}{\dot{m}_{\text{gas}}}. \quad (11.3)$$

**Table 11.2** Nomenclature

$a$	Speed of sound, m/s
$A_{\text{thr}}$	Nozzle throat area, mm <sup>2</sup>
$c$	Helium mass fraction
$c_p$	Isobaric specific heat, kJ/(kg·K)
$C_{\text{tot}}$	Total costs of 1 kg deposited material, \$
$F_{\text{gas}}$	Inverse gas flow factor, 3600 m/ $\sqrt{\text{K}}$ s
$\gamma$	Specific heat ratio
GL	Geometric loss factor
HL	Heat loss factor
$M$	Mach number
$\dot{m}_{\text{gas}}$	Gas flow rate of heated main gas stream, kg/h
$\dot{m}_{\text{pwd}}$	Powder feeding rate, kg/h
$P$	Gas stagnation pressure, MPa
$R$	Specific gas constant, J/(kg·K)
$\rho_1$	Gas density at nozzle exit, kg/m <sup>3</sup>
$\rho_{\text{gas}}$	Gas density, kg/m <sup>3</sup>
$S_{\text{anc}}$	Total electric power consumption of anything but gas heating, kW
$t_{\text{off}}$	Total duration of gas flow without powder flow per kilogram of deposited material, h
$t_{\text{on}}$	Total duration of powder flow per kilogram deposited material, h
$t_{\text{run}}$	Total duration of gas flow per kilogram deposited material, h
$T$	Gas stagnation temperature, K
$T_{\text{amb}}$	Gas inlet temperature, K
$U_{\text{elc}}$	Electrical energy price, \$/kWh
$U_{\text{hr}}$	Total hourly rate, \$/h
$U_{\text{gas}}$	Gas price, \$/kg
$U_{\text{pwd}}$	Powder price, \$/kg
$v_1$	Gas velocity at nozzle exit, m/s
$v_{\text{gas}}$	Gas velocity, m/s
$v_p$	Particle velocity, m/s
$w$	Powder-to-gas mass loading ratio
$Y_{\text{DE}}$	Deposition efficiency

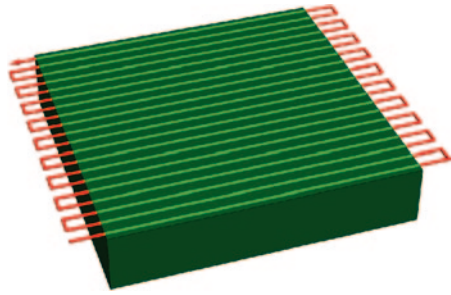
The cumulated powder feeder idle time during deposition of 1 kg material,  $t_{\text{off}}$ , see Fig. 11.9, depends on the application and is an independent model parameter.

At significant temperature differences  $T - T_{\text{amb}}$ , the gas-heating unit produces thermal losses because of convection of surrounding air and radiation from hot surfaces. This can be taken into account by a temperature-dependent “heat loss” factor HL which may reach values up to 0.4 for nitrogen at  $T - T_{\text{amb}} \approx 1000$  K.

Let  $S_{\text{anc}}$  be the total power consumption of the gas pressurizing and CS control units, helium recovery system, dust collector fan, and ancillary equipment like robots.

**Fig. 11.10** In the case of constant nozzle motion speed, the overspray GL (“geometric loss”) is the ratio of the cumulated spray track lengths out of, and on, the work piece

$$GL = \left( \sum_{\text{outside}} \text{track length} \right) / \left( \sum_{\text{inside}} \text{track length} \right)$$



Then the total costs for depositing 1 kg material by CS are given by the generic cost function (Stier 2014):

$$C_{\text{tot}} = \frac{1+GL}{Y_{\text{DE}}} \left[ U_{\text{pwd}} + \frac{1}{w} \frac{t_{\text{run}}}{t_{\text{on}}} \left( U_{\text{gas}} + \frac{U_{\text{hr}}}{\dot{m}_{\text{gas}}} + \frac{1+HL}{3600} c_p (T - T_{\text{amb}}) U_{\text{clc}} \right) \right] + S_{\text{anc}} t_{\text{run}} U_{\text{clc}}. \quad (11.4)$$

Equation 11.4 applies to all spray powders, propellant gases, any “high pressure CS,” “low pressure CS,” LPGDS (Maev and Leshchynsky 2008), “vacuum CS” (Fan et al. 2006), aerosol deposition (Akedo 2008), or kinetic metallization system (Gabel 2004), and to all kinds of application, such as coating, restoration, additive manufacturing, near-net forming.

### Worked Example 1

The generic cost function Eq. 11.4 is used to calculate the costs per piece for the use case presented in Fig. 11.1. Equation 11.4 returns the costs for depositing 1 kg material. In the use case, the mass of deposited material is 1.125 kg per work piece, as calculated from the deposit volume and material density according to Fig. 11.1. Hence, the costs according to Eq. 11.4 will have to be multiplied by 1.125. For the same reason, the temporal durations occurring in Eq. 11.4 need to be divided by 1.125 when taken from Fig. 11.1. Thus, the time needed to deposit 1 kg is  $t_{\text{run}} = 0.32 \text{ h} / 1.125 = 0.286 \text{ h}$ . The spreadsheet assumes  $t_{\text{on}} = t_{\text{run}}$ . Note, the ratio  $t_{\text{run}} / t_{\text{on}}$  is independent of the work piece mass.

Further input parameters for Eq. 11.4 are directly read from Fig. 11.1: The gas used is nitrogen, that is,  $c_p = 1.13 \text{ kJ/kg K}$  (from the literature),  $T = 773.15 \text{ K}$ ,  $U_{\text{pwd}} = 100 \text{ \$/kg}$ ,  $U_{\text{gas}} = 0.14 \text{ \$/kg}$ ,  $U_{\text{clc}} = 0.15 \text{ \$/kWh}$ ,  $w = 0.0467$ ,  $Y_{\text{DE}} = 0.7$ , and the overspray is  $GL = 0.1$ . The gas flow rate is  $\dot{m}_{\text{gas}} = 94.1 \text{ normal cubic meter per hour (NCMH)} \times 1.25 \text{ kg/m}^3 = 117.6 \text{ kg/h}$ , using the density of nitrogen at the norm conditions 273.15 K and 101,325 Pa.

Assume a gas inlet temperature  $T_{\text{amb}} = 293.15 \text{ K}$ ,  $HL = 0.10$ , and  $S_{\text{anc}} = 17.5 \text{ kW}$  for ventilation and pressure booster.



The hourly rate  $U_{hr}$  is not explicitly given by Fig. 11.1 but can be calculated from the displayed numbers as described above: The CS utility is operated during  $2000 \text{ h} \times 75\% = 1500 \text{ h}$  per year, taking into account the available time per year (2000 h) and the system utilization rate (0.75). The yearly depreciation cost is calculated by the CRF method, Eq. 11.1, with  $\text{CRF} = 0.0838$ , and is US\$ 50,260. The yearly expenses for administration, rent, and maintenance (=5% of capital) are US\$ 150,000, US\$ 100,000, and US\$ 45,000, respectively. The total of the four costs (US\$ 345,260), divided by the annual productive hours (1500 h) is the equipment hourly rate, 230 \$/h. To this, the hourly labor rate (75 \$/h) is added, resulting in  $U_{hr} = 305 \text{ $/h}$ . With these numbers, Eq. 11.4 returns  $C_{tot} = 251 \text{ $/kg}$ . By multiplication with 1.125, the mere CS process costs US\$ 282 per work piece.

This price covers all expenses related to the actual spraying, but does not include preparation costs. Obviously, preparation costs cannot be derived from CS process parameters so that they cannot be calculated by a generic cost function. The spread sheet in Fig. 11.1 takes into account such additional costs explicitly: Per work piece, in average  $8/100 + 0.2 = 0.28 \text{ h}$  are spent for pre-spray setup and setup per piece, respectively. Multiplied by  $U_{hr}$ , this time costs another US\$ 85, so that the total costs per piece are US\$ 367. This total contains US\$ 1.79 electricity costs, that is, 0.5%.

For expensive powders, or expensive gases, electricity costs can be neglected, as suggested by the above example. This allows for a significant simplification of Eq. 11.4:

$$C_{tot} \approx \frac{1 + \text{GL}}{Y_{DE}} \left[ U_{\text{pwd}} + \frac{1}{w} \frac{t_{\text{run}}}{t_{\text{on}}} \left( U_{\text{gas}} + \frac{1}{\dot{m}_{\text{gas}}} U_{\text{hr}} \right) \right]. \quad (11.5)$$

Equation 11.5 is specific to expensive spray powders (prices  $U_{\text{pwd}} \geq 100 \text{ $/kg}$ ) or expensive gases (with significant helium content) but generally valid otherwise. Against intuition, the gas costs per kilogram deposited material do not depend on the gas flow rate  $\dot{m}_{\text{gas}}$ , but the equipment and labor costs do. This is due to the process duration effect explained above. Using Eq. 11.3, the gas flow rate in Eq. 11.5 can be substituted by the powder feeding rate:

$$C_{tot} \approx \frac{1 + \text{GL}}{Y_{DE}} \left[ U_{\text{pwd}} + \frac{t_{\text{run}}}{t_{\text{on}}} \left( \frac{U_{\text{gas}}}{w} + \frac{U_{\text{hr}}}{\dot{m}_{\text{pwd}}} \right) \right]. \quad (11.6)$$

Equations 11.5 and 11.6 allow the identification of the main cost factors of CS and to find ways of minimizing those.

CS, kinetic metallization, and aerosol deposition systems are operated at pressures sufficient to produce transonic flow in the nozzle throat, that is, the nozzle throat is choking the gas flow. Hence, the gas flow rate  $\dot{m}_{\text{gas}}$  is equal to the critical

mass flow rate through the nozzle. The critical mass flow rate is known to depend on the nozzle throat orifice cross-sectional area  $A_{\text{thr}}$  and the gas stagnation properties  $P$  and  $T$  in the following way:

$$\frac{1}{\dot{m}_{\text{gas}}} = F_{\text{gas}} \frac{\sqrt{T}}{A_{\text{thr}} P}. \quad (11.7)$$

Herein,

$$F_{\text{gas}} = \frac{\sqrt{R/\gamma}}{3600} \left( \frac{2}{\gamma+1} \right)^{(\gamma+1)/2(1-\gamma)} \quad (11.8)$$

is the inverse flow factor and depends on the kind of gas. The unit of  $F_{\text{gas}}$  is  $3600 \text{ m}/\sqrt{\text{K}} \text{ s}$  (the factor 3600 is for unit conversion from s to h).  $R$  is the specific gas constant and  $\gamma$  the isentropic exponent of the propellant gas. Equation 11.7 relates the CS costs to the primary process parameters  $P$  and  $T$ : Substituting Eqs. 11.2 and 11.7 in Eq. 11.5 yields

$$C_{\text{tot}} \approx \frac{1+\text{GL}}{Y_{\text{DE}}} \left[ U_{\text{pwd}} + \frac{1}{w} \left( 1 + \frac{t_{\text{off}}}{t_{\text{on}}} \right) \left( U_{\text{gas}} + F_{\text{gas}} \frac{\sqrt{T}}{A_{\text{thr}} P} U_{\text{hr}} \right) \right]. \quad (11.9)$$

Herein, electricity costs are neglected by assuming expensive powders or gases. For capacity planning, the process duration can be calculated from Eq. 11.2 in conjunction with one of the following three alternative expressions:

$$t_{\text{on}} = \frac{1+\text{GL}}{\dot{m}_{\text{pwd}} Y_{\text{DE}}} = \frac{1+\text{GL}}{\dot{m}_{\text{gas}} w Y_{\text{DE}}} = \frac{1+\text{GL}}{w Y_{\text{DE}}} F_{\text{gas}} \frac{\sqrt{T}}{A_{\text{thr}} P}. \quad (11.10)$$

An advantage of the cost function Eq. 11.9 is that it involves variables which are comparably easy to estimate up front for an intended CS application: GL is a ratio of possibly unknown values which is easier to estimate than those values themselves.  $t_{\text{off}}$  depends more on the article produced than on any final CS process parameters.

### Worked Example 2

Equation 11.9 is applied to the use case presented in Fig. 11.1. For nitrogen,  $F_{\text{gas}} = 0.0071$  in units of  $3600 \text{ m}/\sqrt{\text{K}} \text{ s}$ .  $P = 4 \text{ MPa}$  and  $A_{\text{thr}} = 5.73 \text{ mm}^2$  (circular cross section). The other input parameters are given in Example 1,  $t_{\text{off}} = 0$ . With these numbers, Eq. 11.9 returns  $C_{\text{tot}} \approx 249 \text{ \$/kg}$ , or US\$ 280 per work piece for the mere CS process. Adding the US\$ 85 for setup times gives total costs per piece of US\$ 366. The neglected electricity costs are US\$ 1.79 per work piece, that is, 0.5%. The process duration for deposition of 1 kg is  $t_{\text{run}} = 0.286 \text{ h}$  according to Eqs. 11.2 and 11.10, so it will be 0.322 h per piece.

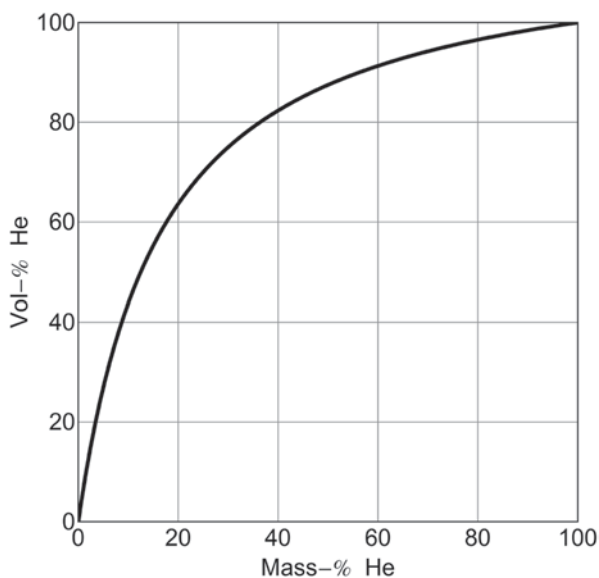
For  $P$ ,  $T$ , and  $w$  typical values may be assumed.  $Y_{DE}$  may be determined from inexpensive experiments, as described above. The coefficients  $A_{thr}$ ,  $F_{gas}$ ,  $U_{gas}$ ,  $U_{pwnd}$ , and  $U_{hr}$  are known.

## 11.6 Gases for CS

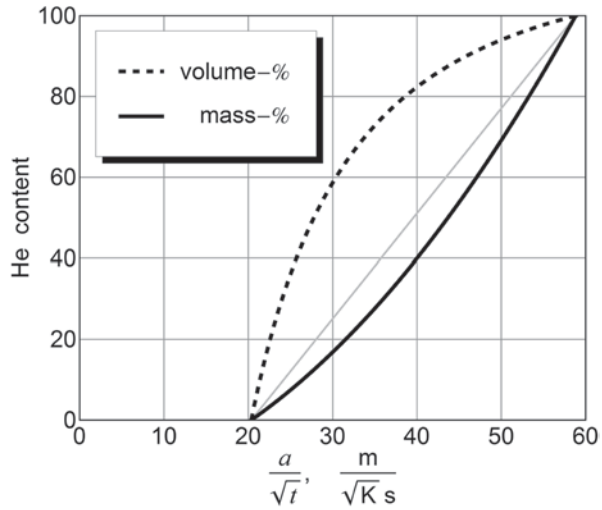
The requirements to CS propellant gases are that they possess a high speed of sound  $a$  and that they are neither inflammable, explosive, or toxic nor prohibitively expensive. In addition, nonoxidizing gases are preferred in many applications. Therefore, helium (He), nitrogen ( $N_2$ ), air, and their mixtures are feasible propellant gases for CS, as well as superheated steam. The technical properties of superheated steam as a CS propellant gas lie between those of  $N_2$  and He while air has thermodynamic properties similar to  $N_2$ . A consideration of binary mixtures of  $N_2$  and He will therefore capture the characteristics of all relevant propellant gases for CS.

The relation between the He mass fraction and the He volume (or mole) fraction in a blend of He and  $N_2$  is nonlinear, as shown in Fig. 11.11. Those technical and economic properties of He- $N_2$  mixtures which are relevant to CS depend more linearly on the He mass fraction  $c$  than on the He volume fraction: The dependence of the gas flow speed  $v_{gas}$  on  $c$  exhibits less deviation from linearity than the dependence of  $v_{gas}$  on the He volume fraction, as shown in Fig. 11.12. The same applies

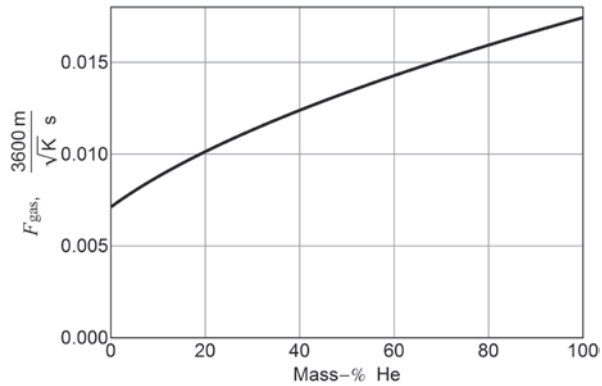
**Fig. 11.11** Relation between the He mass fraction  $c$  and the volume, or mole, fraction of a binary He- $N_2$  mixture



**Fig. 11.12** Relation between the sound velocity  $a$  at temperature  $t$  and the He content for binary He–N<sub>2</sub> mixtures. The gray straight line visualizes a hypothetical linear relation, as a guide to the eye



**Fig. 11.13** Dependence of the inverse flow factor  $F_{\text{gas}}$  on the He mass fraction  $c$  for binary He–N<sub>2</sub> mixtures. Numeric values of  $F_{\text{gas}}$  are 0.0071 for N<sub>2</sub> and 0.0174 for He

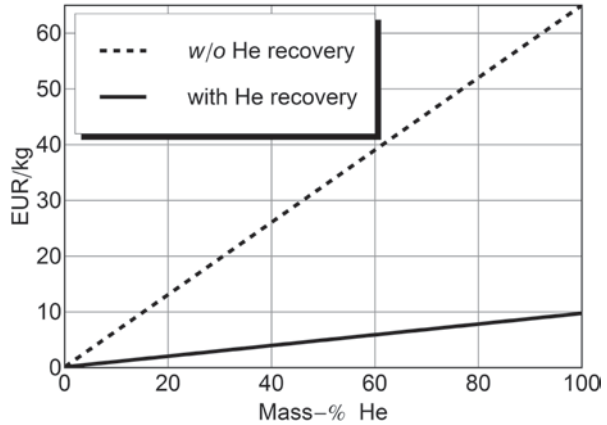


for the inverse flow factor  $F_{\text{gas}}$  shown in Fig. 11.13. Furthermore, the highly cost-relevant parameter  $w$  refers to mass flow rates (Eq. 11.3). Therefore, the He mass fraction  $c$  ( $0 \leq c \leq 1$ ) is preferred over the volume (or mole) fraction for the purpose of cost analysis, and the costs of gas per unit mass are preferred over the costs per unit volume. Coarse estimates for the gas price  $U_{\text{gas}}(c)$  for private industry are shown in Fig. 11.14 for new and recycled He, respectively.

### 11.7 Cost Factors of CS

Given the powder price and the hourly rate, the costs per kilogram deposited material depend on the application-specific process parameters  $GL$  and  $t_{\text{off}}$ ; flow parameters  $P$ ,  $T$ , and  $w$ ; propellant gas properties  $F_{\text{gas}}$  and  $U_{\text{gas}}$ ; particle bonding characteristic property  $Y_{\text{DE}}$ ; and equipment (nozzle) parameter  $A_{\text{thr}}$ .

**Fig. 11.14** Gas price  $U_{\text{gas}}$  dependence on the He mass fraction  $c$ . The solid line refers to a He recovery system with 85% capture efficiency. The  $N_2$  price refers to a liquid  $N_2$  supply with a pressure boost system (e.g., Linde PRESUS).  $N_2$  from cylinder bulk packs is roughly ten times as expensive which, still, is small compared to the He costs. *w/o* without



Obviously,  $GL$  and  $t_{\text{off}}$  have to be as small as possible, as they represent operation modes producing costs without material deposition. The flow parameters  $P$ ,  $T$ , and  $w$  deserve deeper consideration. On first look, Eq. 11.9 suggests that for low process costs both  $Y_{\text{DE}}$  and  $w$  ought to be large. Second, the variance of  $U_{\text{gas}}(c)$  is one order of magnitude larger than that of  $w$ , so a cost analysis needs to include the effect of  $U_{\text{gas}}$ , that is, of  $c$ . Moreover, there is a negative correlation between  $Y_{\text{DE}}$  and  $w$ . Therefore, the minimal costs in general will realize a compromise between the powder and gas costs.

**Worked Example 3**

In the use case of Example 2, nitrogen is replaced by helium, that is,  $U_{\text{gas}} = 30.00$  \$/kg and  $F_{\text{gas}} = 0.0174$  (in units of  $3600 \text{ m}/\sqrt{\text{K s}}$ ). Feeding powder at  $2.5 \text{ kg/h}$  results in a mass loading ratio  $w = 5.3\%$ , as calculated from Eqs. 11.3 and 11.7. Assume that the higher gas velocity obtained by helium (see Fig. 11.12) leads to a DE increase from  $0.7$  to  $Y_{\text{DE}} = 0.95$ . Equation 11.9 now returns  $C_{\text{tot}} \approx 914$  \$/kg, or US\$ 1028 per work piece for the mere CS process. So, the CS process has become a factor 3.7 more expensive than in Example 2, only by using helium ( $c = 1$ ) instead of nitrogen ( $c = 0$ ). Adding US\$ 85 for setup costs gives a total price of US\$ 1113 per piece.

**11.7.1 Gas Stagnation Properties**

To analyze the roles of  $P$  and  $T$ , consider their effect on the particle velocity and acceleration near the nozzle exit. The accelerating force on particles is proportional to

$$\rho_{\text{gas}}(v_{\text{gas}} - v_p) |v_{\text{gas}} - v_p|, \tag{11.11}$$

where  $v_p$  is the particle velocity and  $\rho_{\text{gas}}$  is the gas density. Assuming 1D, isentropic expansion in a full-flowing nozzle (i.e., at sufficient pressure), the gas velocity at the nozzle exit is

$$v_1 = M \sqrt{\gamma R T / \left(1 + \frac{\gamma - 1}{2} M^2\right)}, \quad (11.12)$$

where  $M$  is the nozzle Mach number. The corresponding gas density is

$$\rho_1 = \frac{P}{RT} \left(1 + \frac{\gamma - 1}{2} M^2\right)^{1/(1-\gamma)}. \quad (11.13)$$

From Eqs. 11.11 to 11.13, the following conclusions can be drawn:

The velocity  $v_{\text{gas}}$  originates from  $T$  and is independent of  $P$ .

The particle acceleration force is proportional to  $P$ .

Higher  $M$  produce both higher  $v_{\text{gas}}$  and lower  $\rho_{\text{gas}}$ . Due to this ambivalence, an optimal nozzle Mach number exists for given gas and powder.

According to Eq 11.9, higher  $P$  lead to lower costs. Large stagnation pressures  $P$  are, thus, favorable from both the technical and the economic point of view. Therefore,  $P$  normally can be set as large as technically possible. In case the powder feeding rate needs to be constrained, it is recommended to reduce the gas flow by shrinking the nozzle throat, rather than by reducing the pressure.

As also can be seen from Eq. 11.9, higher  $T$  leads to growing equipment costs. Not even included here is the potential side effect on the hourly rate, that frequent operation at high temperatures may reduce the longevity of the equipment. On the other hand, higher  $T$  normally also lead to larger DE. Hence, the overall influence of increasing gas temperature on the process costs is ambivalent.  $T$  should, thus, be chosen as large as necessary for sufficient particle deposition and bonding strength.

In most of the presently available CS systems,  $T$  is a mixing temperature obtained by injection of cool powder feeding gas (with powder) into the hot main gas flow heated to the displayed temperature. This results in a lower stagnation temperature and a higher gas flow (except, for LPGDS systems where the injection occurs downstream of the nozzle throat). The required flow rate of powder feeding gas is related to the powder feeding rate, so that the mixing temperature  $T$  eventually depends on  $w$ . If the powder feeding gas has a different He content than the main gas, then even  $c$  may depend on  $w$ . The limited electrical heating power of an actual CS system may impose a constraint on the possible combinations of  $T$ ,  $\dot{m}_{\text{gas}}$ , and  $c$ . Such effects can be considered when the cost optimization goes into detail.

### 11.7.2 Mass Loading Ratio

Feeding powder into the gas results in a deceleration of the flow. This particle loading effect on the flow speed imposes an upper bound on  $w$  because lower particle

impact velocities  $v_{pi}$  result in lower DE. At the opposite end, decreasing  $w$  will allow it to dominate the costs because  $C_{tot}$  is asymptotically proportional to  $1/w$  for  $w \rightarrow 0$ . Mass loading ratios have been reported in the interval from 1 to 30%. Thereby,  $w \approx 3 \dots 5\%$  may be considered typical for CS using  $N_2$ , whereas larger ratios may be affordable with He, or gas mixtures containing significant He mass fractions  $c$ .

From the cost point of view,  $U_{gas}/w$  should be minimal at given powder feeding rate and DE, as can be seen from Eq. 11.6. Depending on the world region, the  $N_2$  supply form, and market conditions, 1 kg He is 75–500 times as expensive as 1 kg  $N_2$ , so that the gas price  $U_{gas}(c)$  is approximately proportional to the He mass fraction  $c$ , see Fig. 11.14. Hence,  $c/w$  should be minimal for minimizing  $C_{tot}$  at given  $\dot{m}_{pvd}$  and  $Y_{DE}$ . However,  $c$  has influence on both the affordable mass loading ratio and the achievable DE, so that the cost optimal He concentration is not easily determined, in general. Only if pure nitrogen yields high DE and the specified deposit properties, the cost optimal He concentration is certainly  $c=0$ .

#### Worked Example 4

In the use case of Example 3, the powder feeding rate is doubled (5 kg/h) so that  $w = 10.6\%$ . Everything else remains unaltered, in particular the DE (by assumption). According to Eq 11.9,  $C_{tot} \approx 515$  \$/kg which corresponds to US\$ 579 per work piece, for the mere CS process. So, the doubled mass loading ratio results in 44% cost reduction and yields a piece price of US\$ 665 including setup costs.

The CS process is still a factor 2.7 more expensive than in Example 2. For a cost break-even with Example 2, the mass loading ratio would have to be increased to 32% while maintaining a DE of 95%. This is not necessarily realistic. The use of helium does not seem to pay off in this example because a relatively high DE (70%) is already reached using nitrogen. Only if the coating quality obtained with nitrogen was unacceptable, helium would *have to* be used, regardless of the cost increase.

## 11.8 Cost Optimization of CS

The generic cost function possesses a valley between two regions of high costs: At low  $c$  and high  $w$  the gas is overloaded with powder which results in flow deceleration and reduced DE. Small values of  $Y_{DE}$  result in exceedingly high total costs, see Eq. 11.6. On the contrary, at high  $c$  and low  $w$  the powder acceleration capacity of the gas is not exhausted which results in exceedingly high gas costs, again see Eq. 11.6. Near a certain optimal ratio of  $c$  and  $w$ , the total costs become minimal. Then, the acceleration capacity of the gas is fully used while avoiding significant powder loss due to flow deceleration.

In case a He recovery system is used,  $U_{hr}$  will increase because of the higher capital costs while  $U_{gas}$  will decrease due to the recycling. By recycling of He, the valley of the cost function may become deeper and wider, in spite of increased investment and potentially a reduced number of annual productive hours. This would allow for additional flexibility in choosing the CS process parameters. A He recovery system would pay off in high volume production, even when using gas blends with significant contents of nitrogen. This can be seen from comparing the two summands in the round brackets in Eq. 11.5: For present commercial high flow rate CS systems the term  $U_{hr}/\dot{m}_{gas}$  typically assumes values below 10 €/kg. Any reduction of  $U_{gas}$  by this order will compensate the increase of the equipment hourly rate, as caused by a He recovery system. In view of He prices around  $U_{gas} \approx 65$  €/kg this option appears realistic. Another argument in favor of He recovery is the fact that He is a finite and nonrenewable natural resource.

### Worked Example 5

Assume the use case of Example 3 and add US\$ 1,100,000 to the equipment capital cost for a He recovery system with 70% capture efficiency. Then, the yearly depreciation cost increases to US\$ 142,403 (Eq. 11.1) and maintenance costs US\$  $2 \text{ M} \times 5\% = \text{US\$ } 100,000$  per year. The total hourly rate thus increases by US\$ 98, to  $U_{hr} = 403$  \$/h. Due to the gas recycling,  $U_{gas} = 30.00 \times (1 - 0.7) = 9.00$  \$/kg. Under these conditions, the total piece price will be US\$ 675. Compared with Example 3 where all new He is used, the recycling eventually saves 39% of the costs. In the given example, spraying with recycled He still is more expensive than spraying with nitrogen. However, if the deposit quality obtained with nitrogen was unacceptable, helium recovery would be economically mandatory.

## 11.9 Concluding Remarks

A framework for CS cost estimation has been presented. The costs have a plain generic structure which applies to all present types of CS systems and kinds of application. Comfortably, this allows an assessment of the economic viability of an intended application before knowing many spray process details.

The principle cost categories of materials, labor, and overhead have been defined and broken down into individual components. The method to determine the cost contribution of each component has been described. These components have been incorporated into a spreadsheet (Fig. 11.1). The spreadsheet utilizes input values, such as DE, powder cost, equipment cost, and coating volume to calculate the cost of the completed products. The calculations of the spreadsheet example are straightforward and can be done by readers either by hand calculation or by computer, for example Windows Excel. Additionally, the authors may be contacted for assistance.



We saw that individual parameters can have significant cost impact and that the judicious combination of these parameters can result in cost savings. The influence of gas on cost is extreme, due to a two order of magnitude difference in gas purchase price between nitrogen and helium. Helium recovery pays off in high volume production. Clearly, the use of nitrogen is favored, but at times, helium must be used for a desired result. Helium–nitrogen blends possess economic potential, and the generic cost function (Eq. 11.9) is useful for determination of the cost optimal helium concentration for a given application. Powder feed rate is often overlooked as a cost driver, but must be carefully understood and controlled to achieve a specified result at a minimum cost. Using high gas stagnation pressures is generally favorable in CS.

There are competing technologies that can be applied to most applications. As CS applications are being developed, it is important to be able to assess the commercial viability of the application. In addition to quality, relative cost is critical for this assessment.

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