CARBON/CARBON TRAYS FOR REDUCED OPERATING COST OF SINTERING FURNACES

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ABSTRACT

Sintering furnace technicians must balance an array of variables to optimize profitability of their operations. Sintering trays based on carbon/carbon composite technology enable new dimensions of performance with direct effects on operating costs. In order to quantify the potential benefits of this innovation, an operating cost calculator has been developed for a mesh belt sintering furnace with inputs for production rate, power, atmosphere, and consumables. The direct operating costs for three scenarios are compared: graphite sintering trays, ceramic sintering trays, and carbon/carbon composite sintering trays. The model demonstrates the potential annual savings due to reduced power requirements when using carbon/carbon composite sintering trays. In addition, cost savings related to increased belt life, increased throughput, and reduced cost of quality will be presented.

INTRODUCTION

When process technology advances, it is typically the challenge of operations to determine when the investment will be made to upgrade manufacturing equipment. The decision can depend on many factors, such as the age and condition of existing equipment, efficiency of the equipment, cost of new technology, and the return on investment with new technology. Ultimately, new equipment must pay for itself in a predetermined timeframe and provide ongoing benefit.

Sintering furnaces have benefitted from technological advances over the years. Whether it be in construction (new materials and designs), atmosphere (e.g., nitrogen/hydrogen), or power controls, these improvements enabled reduction of total cost of operations. Sintering furnaces must be operated efficiently with respect to energy, consumables, throughput, labor, and yield. Each of these cost contributors must be minimized and played against one another over the lifetime of the furnace. The furnace itself incurs costs associated with preventive maintenance aimed at optimizing the lifetime of the furnace.

A key consumable in the sintering process affecting all cost parameters is the choice of sintering tray material. Sintering trays contribute to direct operating cost of a sintering furnace through:

1. Thermal load (energy)
2. Belt life (consumables)
3. Muffle life (consumables)
4. Belt loading constraints (throughput)
5. Tray Lifetime (consumables)
6. Quality (labor, yield)

The selection of tray material composition must go beyond purchase price and incorporate other dimensions of performance to completely understand the return on investment for each option. Higher cost can often be balanced against longer life, improvements in quality, or benefits in other cost categories. This paper will examine the effect of tray material choice on various cost elements, calculating annual direct operating cost for three tray materials: graphite, ceramic, and carbon/carbon (c/c) composite.

FURNACE MODEL

The cost model developed in this paper is based on a seven zone, twenty-four inch wide belt furnace. The furnace is operated with a peak temperature of 2050°F in a gas atmosphere composition of 10% hydrogen and 90% nitrogen. The belt speed is assumed to be six inches per minute, and the furnace output is 900 lbs/hour (408 kg/hour). The furnace is operated fifty weeks on a 24/5 basis, sintering parts with a FC-0208 composition.

Three tray materials are examined: extruded graphite, ceramic, and carbon/carbon composite. The word 'ceramic' is often used to describe various purity grades of alumina, as well as cordierite body ceramic trays. For the purposes of this paper, 'ceramic' will refer to sintered alumina with 91% purity. Many of the key parameters for alumina – specific gravity, specific heat capacity, thermal shock resistance, fracture toughness, and thermal conductivity – are similar for cordierite, so statements regarding alumina are generally applicable to cordierite as well. Carbon/carbon composite refers to a composite of carbon fibers with a carbon matrix, essentially fiber-reinforced graphite.

The tray dimensions, as well as the properties of these materials, are provided in Table 1. Whereas the graphite and ceramic trays are shown having 0.375 inch (0.95 cm) thickness, the enhanced fracture toughness (Figure 1) of carbon/carbon trays enables them to be manufactured with a reduced thickness of 0.200 inch (0.51 cm). This reduces thermal and physical mass of the tray.

Table 1: Physical Properties of Tray Materials

Tray Properties	Extruded Graphite	Ceramic	Carlisle C/C HL grade	units (SI units)
Length	8.5 (21.59)	8.5 (21.59)	8.5 (21.59)	in (cm)
Width	17 (43.18)	17 (43.18)	17 (43.18)	in (cm)
Thickness	0.375 (0.95)	0.375 (0.95)	0.2 (0.51)	in (cm)
Specific gravity	0.063 (1.74)	0.105 (2.91)	0.059 (1.63)	lb/cu-in (g/cc)
Weight	3.4 (1.55)	5.7 (2.59)	1.7 (0.78)	lb (kg)
Specific heat capacity	0.31 (1.30)	0.21 (0.88)	0.31 (1.30)	BTU/lb/°F (kJ/kg/K)
Heat capacity	1.06 (2.01)	1.19 (2.27)	0.53 (1.01)	BTU/°F (kJ/K)
Thermal Conductivity	50.0	2.3	50.0	W/m/K
Coefficient of Thermal Expansion	3.5 [RT-200°C]	8	1 [RT-1000°C]	$x10^{-6}$/°C ($x10^{-6}$/K)
Fracture Toughness	1.4	3.5	43	MPa-$m^{1/2}$
Thermal Shock Parameter	98.1	0.8	115.4	n/a

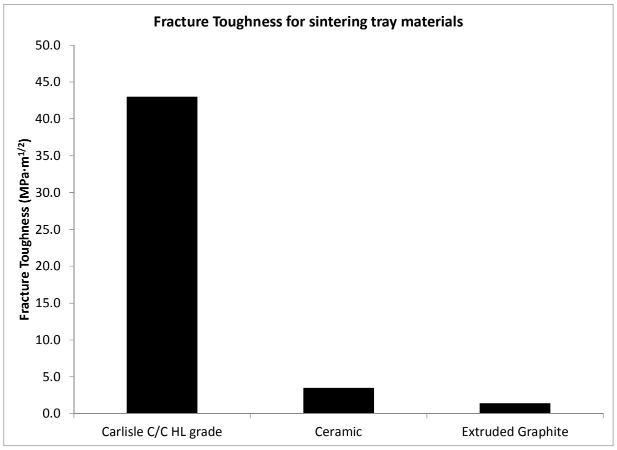


Figure 1: Fracture Toughness of Tray Materials

A review and comparison of these properties is useful to understand the effect they have on the sintering application. As previously mentioned for carbon/carbon, fracture toughness enables thinner trays to be utilized. The result of this reduced thickness is lower mass on the belt, contributing to longer belt life and/or enabling additional throughput. Note the difference in weight between the three trays, with carbon/carbon composite trays being 50% of the graphite tray weight and 30% of the ceramic tray weight. The product of specific heat capacity and weight is the heat capacity, a measure of how much thermal energy must be input or removed to raise or lower the temperature of the material. In the case of carbon/carbon composite trays, the heat capacity is at least half the value for either the graphite or ceramic trays. During the delubrication of compacted parts, low heat capacity enables carbon/carbon composite trays to reach temperature quickly. This allows compacted parts to reach delubrication temperature earlier, and time at temperature is critical for complete removal of lubricating additives. Heat capacity is also vital during cool down of sintered parts. In tray materials with high heat capacity, the temperature between the top and bottom of the tray can vary and lead to variation in the microstructure, and therefore hardness, of parts sintering on the trays. Sintering trays with the lowest heat capacity enable quicker cool down of sintered parts and reduce thermal gradients within parts.

COST APPROACH

Direct operating costs for a sintering furnace can be determined on an hourly basis for a given set of assumptions (e.g., sintering tray composition) and compared to the same values using a different set of assumptions. In addition, an annualized operating cost can be calculated based on these hourly costs to illustrate the long term impact of sintering tray composition. Seven cost categories will be examined in this discussion:

1. Depreciation
2. Throughput
3. Power
4. Consumables
5. Atmosphere
6. Labor
7. Quality

Depreciation

While the approach to calculating depreciation of capital varies, this discussion will follow the practice of dividing furnace purchase price by expected lifetime operating hours. Assume a furnace purchase price of $550,000. The furnace will be operated fifty weeks per year, five days per week, and twenty four hours per day at an 90% utilization rate. With a conservative lifetime of seven years, the expected operating lifetime of the furnace would be 37,800 hours (Equation 1). Based on these assumptions, a depreciation cost of $14.55/hour can be calculated (Equation 2).

$$Lifetime = 7\ years * 50\ \frac{weeks}{year} * 5\ \frac{days}{week} * 24\ \frac{hours}{day} * 90\%\ utilization = 37{,}800\ hours \qquad \textbf{(1)}$$

$$Depreciation\ Rate = \frac{\$550{,}000}{37{,}800\ hours} = \$14.55/hr \qquad \textbf{(2)}$$

Depreciation Cost/Hour **$14.55/hr**

Throughput

Sintering furnaces can be constrained in their output capability due to weight limitations on wire mesh belts. Furnace operators must balance this constraint against the need for the highest throughput possible. In some cases, trays of parts are staged with a gap between them to reduce the areal weight on the belt. Another approach is to reduce the number of parts on each tray. With carbon/carbon composite trays, the weight reduction associated with thinner trays enables additional parts to be processed. Instead of using the mesh belt weight allowance on tray weight, furnace operators can load more parts and achieve higher throughput. In Table 2, the tray weight throughput in the model furnace is shown for each tray scenario. As tray weight throughput decreases, part weight throughput increases.

Table 2: Throughput Implications of Reduced Tray Weight

Tray Material	Tray Throughput [lbs/hr]	Parts Throughput [lbs/hr]	Parts Throughput [lbs/yr]	Throughput increase (%)	
Ceramic	241	900	4,860,000	-	
Graphite	144	997	5,383,800	11%	over ceramic
C/C Composite	73	1068	5,767,200	7%	over graphite
				19%	over ceramic

Power

The power required to heat a sintering furnace can be generated using electricity or natural gas. In the case of our cost model, electric heating is assumed. The cost of power is then dependent on the price of electrical power ($/kw-hr) and the amount of power (kw-hr) used to raise the furnace contents (insulation, atmosphere, belt, trays, and PM parts) from the preheat zone (200°F) to the high heat zone (2050°F) temperature. A nominal price of $0.08/kw-hr will be assumed for the cost of power. The amount of power required to heat the furnace contents is determined knowing the weight of each item in the furnace, the specific heat capacity of each item, and the difference in temperature between the preheat and high heat zones (Equation 3). In order to determine electricity costs, a conversion factor from BTU/hour to kilowatts is necessary. This value is 0.00029 kilowatts per BTU/hr. In Table 2, the power consumption necessary to heat all furnace contents is presented. As there are three sintering tray materials, the table is divided into columns specific to each tray material.

$$Power\ \left(\frac{BTU}{hr}\right) = Weight\ \left(\frac{lb}{hr}\right) * Specific\ Heat\ Capacity\ \left(\frac{BTU}{lb{\cdot}F}\right) * \Delta T\ (F) \tag{3}$$

Table 3: Power Consumption of Furnace Contents

	Graphite			Ceramic			Carbon/Carbon		
Consumption	**BTU/hr**	**kw**	**$/hr**	**BTU/hr**	**kw**	**$/hr**	**BTU/hr**	**kw**	**$/hr**
Insulation	18,945	5.5	$ 0.44	18,945	5.5	$ 0.44	18,945	5.5	$ 0.44
Parts	228,605	66.3	$ 5.30	228,605	66.3	$ 5.30	228,605	66.3	$ 5.30
Trays	82,564	23.9	$ 1.92	93,701	27.2	$ 2.17	41,756	12.1	$ 0.97
Atmosphere	45,971	13.3	$ 1.07	45,971	13.3	$ 1.07	45,971	13.3	$ 1.07
Belt	229,992	66.7	$ 5.34	229,992	66.7	$ 5.34	229,992	66.7	$ 5.34
TOTAL HEAT LOAD	606,076	175.8	$ 14.06	617,213	179.0	$ 14.32	565,268	163.9	$ 13.11

Power Cost/Hour (graphite trays)	**$15.56/hr**
Power Cost/Hour (ceramic trays)	**$15.82/hr**
Power Cost/Hour (carbon/carbon trays)	**$14.62/hr**

As the power consumption is compared across Table 3, it is notable that the hourly cost for power to heat the carbon/carbon composite trays is approximately half the cost for the other two tray materials.

Consumables

A variety of typical sintering furnace consumables, as well as their cost elements, is summarized in Table 4. The cost of carbon/carbon composite trays has conservatively been set at ten times the cost of either graphite or ceramic trays for the purposes of this paper. An annual cost is calculated by dividing replacement cost by twelve months and multiplying this by the expected life in months for the consumable item (Equation 4). Finally, the annual costs are totaled and divided by the number of operating hours in a year. Three different consumable cost/hour results are presented, one for each tray material. The lifetime for the graphite and ceramic trays is typically controlled by breakage, due to the low fracture toughness of these materials. In contrast, the carbon/carbon composite trays do not suffer from this phenomenon. The lifetime for the carbon/carbon composite trays has been conservatively set at twenty four months, although the trays may be refurbished and could theoretically last several years without breakage.

$$Annual\ cost\ (\$) = Expected\ life\ (months) * \frac{Replacement\ cost\ (\$)}{12\ months} \tag{4}$$

Table 4: Cost Elements for Consumable Items

CONSUMABLES				
	Life (months)	Replacement Cost	Hourly Cost	Annual Cost
Belt	12	$ 10,000	$ 0.26	$ 10,000
Trays - graphite (60)	6	720	$ 0.04	$ 1,440
Trays - ceramic (60)	6	720	$ 0.04	$ 1,440
Trays - carbon/carbon composite (60)	24	7,200	$ 0.10	$ 3,600
First cooler	18	6,000	$ 0.11	$ 4,000
Coolers	84	6,000	$ 0.02	$ 857
Heating Elements (High Heat)	24	12,000	$ 0.16	$ 6,000
Heating Elements (Pre-Heat)	60	1,200	$ 0.01	$ 240
Thermocouples (2/zone)	3	350	$ 0.04	$ 1,400
Muffle	24	25,000	$ 0.33	$ 12,500
Total Annual Consumable Cost				$ 36,437
Consumable Cost/Hour (Graphite)				$ 6.75
Total Annual Consumable Cost				$ 36,437
Consumable Cost/Hour (Ceramic)				$ 6.75
Total Annual Consumable Cost				$ 38,597
Consumable Cost/Hour (C/C Composite)				$ 7.15

Consumable Cost/Hour (graphite trays) **$ 6.75/hr**

Consumable Cost/Hour (ceramic trays) **$ 6.75/hr**

Consumable Cost/Hour (carbon/carbon trays) **$ 7.15/hr**

Atmosphere

Atmosphere cost is based on two different gas sources, nitrogen and hydrogen, supplied in relative concentrations of 90% and 10% respectively. Assuming a cost per 100 cubic foot hour or ccfh of \$0.70/ccfh for nitrogen and \$2.00/ccfh for hydrogen, as well as a total flow rate of 20.4 ccfh, the cost to supply atmosphere to the furnace can be determined as \$16.93/hour (Equation 5).

$$Atmosphere\ cost\left(\frac{\$}{hr}\right) = 90\% * 20.4\ ccfh * \frac{\$0.70}{ccfh} + 10\% * 20.4\ ccfh * \frac{\$2.00}{ccfh} \qquad (5)$$

Atmosphere Cost/Hour **$16.93/hr**

Labor

While a furnace operator can typically keep more than a single furnace operating, a conservative estimate is to assign one operator per furnace. Labor rates can vary, ranging from \$12.50/hour to \$15.00/hour. For this analysis, a conservative labor rate of \$15.00/hour will be assumed.

Labor Cost/Hour **$15.00/hr**

Quality

Poor quality – also known as scrap, “nonquality”, or parts out of specification – is an overlooked and often understated cost. This is due to the difficulty in quantifying the impact of poor quality, as it frequently affects multiple cost centers. Sintering furnaces generating scrap must process more material to serve customers, leading to scheduling issues and additional expense for powders and all operations through sintering. Typically, some unit of labor expense is necessary for sorting and/or reworking parts. Instead of inspecting a subset of sintered parts, every part must be inspected to ensure conformance. This investigation will not attempt to incorporate this level of detail in cost calculations. Instead, the cost of quality will be integrated in the cost model by reducing the throughput of the furnace by a small and arbitrary percentage to illustrate the effect of quality on annual costs.

DISCUSSION

The various cost categories outlined in section IV are summarized in Table 5, calculating a total direct cost per hour and annual direct operating cost for the three sintering tray materials. The difference in annual direct operating cost between carbon/carbon composite sintering trays and the other materials is shown at the bottom of Table 5 as $\Delta_{C/C}$. Comparing the power and consumables categories, it can be seen that the increased cost of the carbon/carbon composite trays is essentially offset by the power savings from using a thinner tray. This is especially true when switching from ceramic trays to carbon/carbon composite trays, while the investment is not quite repaid for graphite trays based on power savings alone.

Table 5: Direct Operating Cost for Three Tray Materials

	Graphite			Ceramic			Carbon/Carbon	
Cost Component	**$/hr**	**%**		**$/hr**	**%**		**$/hr**	**%**
Depreciation	$ 14.55	21%		$ 14.55	21%		$ 14.55	21%
Atmosphere	$ 16.93	25%		$ 16.93	24%		$ 16.93	24%
Power	$ 15.73	23%		$ 15.99	23%		$ 14.77	21%
Consumables	$ 6.75	10%		$ 7.01	10%		$ 7.15	10%
Labor	$ 15.00	22%		$ 15.00	22%		$ 15.00	22%
Total	$ 68.96			$ 69.49			$ 68.40	
Sintering cost/lb	$ 0.077			$ 0.077			$ 0.076	
ANNUAL								
Pounds produced	4,860,000			4,860,000			4,860,000	
Direct operating cost	$ 372,375			$ 375,225			$ 369,369	
$\Delta_{C/C}$	$ 3,007		$\Delta_{C/C}$	$ 5,857				

As previously discussed, the cost of quality is often minimized, overlooked, or understated when evaluating the profitability of a sintering operation. Scrap can result from many furnacing-related sources. Thermal variation due to high heat capacity sintering trays like thick graphite and ceramic trays can lead to differences in sintered part microstructure, resulting in varying hardness. Thermal lag due to high heat capacity trays in the preheat sections can result in incomplete delubrication. Under certain dewpoint conditions, silica binder leached from ceramic trays can combine with carbon generated by incompletely delubed parts and attack the muffle and belt.[1, 2] Thermal lag due to high heat capacity trays in the cool down sections can generate differences in sintered part microstructure, resulting in hardness variation and internal stresses leading to out-of-round and out-of-flat parts. The lower heat capacity of thin, carbon/carbon composite trays helps alleviate thermal lag issues. In addition, the fiber-reinforced nature of carbon/carbon composite trays means they stay flat even at 0.200” thickness and create a constant reference surface through repeated thermal cycling.

Carbon/carbon composite trays are also significantly free of impurities, having been purified to less than 20 ppm metallic impurities. As mentioned above, ceramic trays may contain silica binder that can leach out from the trays under certain dewpoint conditions, depositing on the muffle, other furnace internal surfaces, and sintering parts. As silica binder leaves the alumina tray, the already low fracture toughness of the tray is further reduced leading to shortened life for the trays. Extruded graphite trays also typically contain impurities on the order of ten times the level found in carbon/carbon composite trays.

If a small part scrap rate of 1% is assumed using graphite or ceramic trays for the reasons discussed above, and the use of a carbon/carbon composite tray eliminates this scrap cause, the cost situation looks like the results shown in Table 6. This reduction in scrap is relative, whether it decreases from 3% to 2% or from 1% to 0% as used in the table below. Comparing the annual cost when using either the graphite or ceramic trays to the cost when using carbon/carbon composite trays, denoted by $\Delta_{C/C}$, it is apparent that the cost savings more than compensates for the initial expense of the higher cost carbon/carbon composites trays.

Table 6: Effect of Scrap on Direct Operating Cost

Scrap Rate	1%			1%			0%	
	Graphite			**Ceramic**			**Carbon/Carbon**	
Cost Component	**$/hr**	**%**		**$/hr**	**%**		**$/hr**	**%**
Depreciation	$ 14.55	22%		$ 14.55	21%		$ 14.55	21%
Atmosphere	$ 16.93	25%		$ 16.93	25%		$ 16.93	25%
Power	$ 14.21	21%		$ 14.47	21%		$ 13.25	20%
Consumables	$ 6.75	10%		$ 6.75	10%		$ 7.15	11%
Labor	$ 15.00	22%		$ 15.00	22%		$ 15.00	22%
Total	$ 67.44			$ 67.70			$ 66.88	
Sintering cost/lb	$ 0.075			$ 0.075			$ 0.074	
ANNUAL								
Pounds produced	4,908,600			4,908,600			4,860,000	
Direct operating cost	$ 367,816			$ 369,241			$ 361,168	
$\Delta_{c/c}$	$ 6,648		$\Delta_{c/c}$	$ 8,072				

Another way of describing the cost benefit of carbon/carbon composite trays over competing tray materials is to determine payback period for the tray investment. In Table 7, the payback period for three scrap reduction values is determined for switching from graphite or ceramic trays to carbon/carbon composite trays. In the case of a 1.0% reduction of scrap resulting from the change, payback for switching from either tray material to carbon/carbon composite is under two years.

Table 7: Payback Period for Carbon/Carbon Composite Trays

Graphite Tray → Carbon/Carbon Composite Tray				**Ceramic Tray → Carbon/Carbon Composite Tray**			
Scrap reduction	**Annual Tray Expense**	**Annual Savings from C/C Tray**	**Payback Period**	**Scrap reduction**	**Annual Tray Expense**	**Annual Savings from C/C Tray**	**Payback Period**
1.0%	$ (3,600)	$ 6,648	14.2 months	1.0%	$ (3,600)	$ 8,072	9.7 months
5.0%	$ (3,600)	$ 21,215	2.5 months	5.0%	$ (3,600)	$ 22,696	2.3 months
10.0%	$ (3,600)	$ 39,424	1.2 months	10.0%	$ (3,600)	$ 40,975	1.2 months

Aside from power savings and quality improvements, there are other benefits when switching to a lighter weight and thinner sintering tray. Belt life can be extended when transporting less weight through the furnace, translating to a lower annual cost from this category. Belt and muffle life can also be extended by avoiding use of silica-containing sintering trays, especially in cases where furnaces are operated close to the dewpoint for silica removal. Again, extending the life of these particularly expensive consumables can further reduce this cost category.

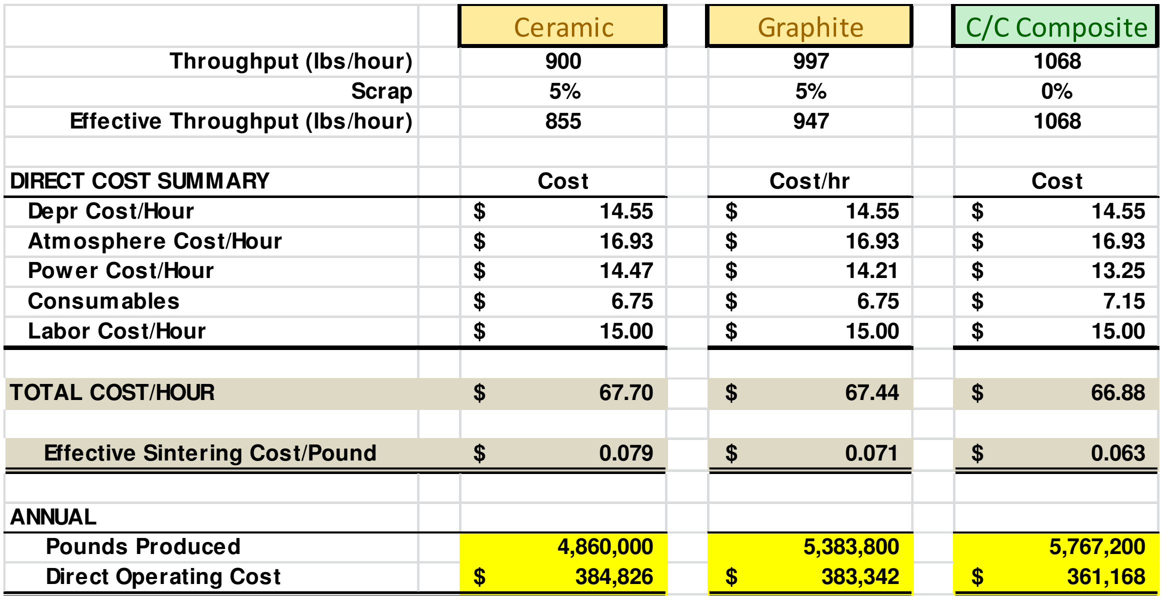
An alternative approach to power savings is to take advantage of reduced belt loading by stacking parts to gain increased throughput. The reduced height of the tray enables clearance for stacking parts. In cases where the combination of tray height and part height are greater than the muffle height, a thinner tray increases the height available within the muffle and opens up potential for taller parts to be sintered in the furnace. When power savings is given up for increased throughput, the extension of belt life due to reduced weight on the belt is sacrificed.

CONCLUSION AND NEXT STEPS

Ultimately, as the PM industry evolves and grows, new technologies are enabling the industry to compete more effectively. The decision to take advantage of these technological improvements must be justified by payback. The upfront cost of outfitting a sintering furnace with thin carbon/carbon composite sintering trays, combined with the power savings associated with their use, results in a total cost comparable to that for either graphite or ceramic sintering trays. The real benefit from upgrading to carbon/carbon composite trays is the potential savings from throughput increases and scrap reduction. Even modest improvements in yield due to use of carbon/carbon sintering trays result in savings equal or greater to the purchase price of the trays. The potential to improve the life of the wire mesh belt and other furnace components provides additional financial benefits. The cost of quality associated with monitoring, managing, and replacing cracked graphite and ceramic trays is now avoidable.

When the fracture toughness of carbon/carbon composite trays is incorporated in the calculation of sintering costs, the true cost includes cost reductions from increased throughput and yield. Table 8 summarizes one scenario for the three tray materials included in this study. The table incorporates the throughput improvement previously discussed and summarized in Table 2, where part throughput increases as tray weight decreases. This throughput value is used to calculate annual part throughput in units of pounds. In addition, Table 8 also calculates an effective throughput for each tray material based on a scrap rate of five percent. The effective throughput is smaller than the furnace throughput, since five percent of the material generated is discarded. The effective throughput is used in the calculation of sintering cost per pound, which increases due to the reduced amount of parts generated within specification. When comparing the annual output and associated direct operating cost for each sintering tray material, it is apparent that carbon/carbon composite trays generate substantially more parts at a lower cost than alternative tray materials.

Table 8: Summary Payback Scenarios



	Ceramic	Graphite	C/C Composite
Throughput (lbs/hour)	900	997	1068
Scrap	5%	5%	0%
Effective Throughput (lbs/hour)	855	947	1068
DIRECT COST SUMMARY	Cost	Cost/hr	Cost
Depr Cost/Hour	$ 14.55	$ 14.55	$ 14.55
Atmosphere Cost/Hour	$ 16.93	$ 16.93	$ 16.93
Power Cost/Hour	$ 14.47	$ 14.21	$ 13.25
Consumables	$ 6.75	$ 6.75	$ 7.15
Labor Cost/Hour	$ 15.00	$ 15.00	$ 15.00
TOTAL COST/HOUR	$ 67.70	$ 67.44	$ 66.88
Effective Sintering Cost/Pound	$ 0.079	$ 0.071	$ 0.063
ANNUAL			
Pounds Produced	4,860,000	5,383,800	5,767,200
Direct Operating Cost	$ 384,826	$ 383,342	$ 361,168

In carbon-sensitive applications, such as soft magnetics and stainless steel formulations, eutectic barrier coatings are usually applied to carbon-based sintering trays like graphite. The same holds true for carbon/carbon composite sintering trays, as they are essentially fiber-reinforced graphite. In separate work, an array of eutectic barrier coatings was evaluated on carbon/carbon composite sintering trays for thermal and chemical stability.[3] Thermally sprayed alumina coatings were among several promising coating technologies evaluated during this study. Thermally sprayed alumina coatings have a thermal expansion mismatch with graphite and eventually spall, requiring recoat. The lifetime of these coatings on graphite is typically around thirty furnace cycles.[4] In contrast, the surface structure of carbon/carbon composite trays has been shown to extend the lifetime of thermally sprayed alumina coatings deposited on them. Recently completed trials demonstrated a lifetime enhancement of six times for carbon/carbon composite trays coated with thermally sprayed alumina compared to graphite trays with the same coating. Work continues on optimizing novel eutectic barrier coatings, as well as assessing lifetime of these coatings in customer furnaces.

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