A Thermodynamic Characterization of Manufacturing Processes

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ABSTRACT

The aim of this paper is to characterize the material and energy transformations that take place in manufacturing processes. The measures used here are energy, and a related property "exergy". We summarize thermodynamic data for three aspects of the manufacturing processes: 1) the energy requirements for the materials used in manufacturing processes, 2) the energy requirements for manufacturing processes themselves, and 3) the efficiency of the material and energy transformations in manufacturing processes.

KEYWORDS

Energy, Exergy, Manufacturing Processes

INTRODUCTION

The main purpose of manufacturing processes is to transform materials into useful products. In the course of these operations, energy resources are consumed and the usefulness of material resources is altered. Each of these effects can have significant consequences for the environment and for sustainability, particularly when the processes are practiced on a very large scale. Thermodynamics is particularly well suited to analyze the magnitude of these effects as well as the efficiency of the transformations. In this paper, we summarize data for three important aspects of manufacturing processes: 1) the energy requirements for the materials used in manufacturing processes, 2) the energy requirements for manufacturing processes themselves, and 3) the efficiency of the material and exergy transformations in manufacturing processes.

Energy (*E*), Enthalpy (*H*), Entropy (*S*), Heat (*Q*), Work (*W*), Temperature (*T*) and Exergy (*B*) are defined in Thermodynamics textbooks and so for brevity are not reviewed here [1-4]. Exergy is used here as the maximum amount of work that could be obtained from a material system in relationship to a well defined reference state (*R*) and is measured in Joules (*J*). All thermodynamic measures require an explicit statement of the system boundaries. This is shown in Figure 1 where we represent the components of a manufacturing process system as : (A) the Manufacturing Process and (B) the Energy Conversion Process for Manufacturing, and (C) The Materials Production Process and (D) the Energy Conversion Process for the Materials Process. Each box represents an open, bulk flow process in steady-state with enthalpy and entropy flows, heat transfer with the environmental reservoir at temperature T_R, and shaft work or energy transfer between the processes. The notation is that of Gyftopoulos and Beretta [1].

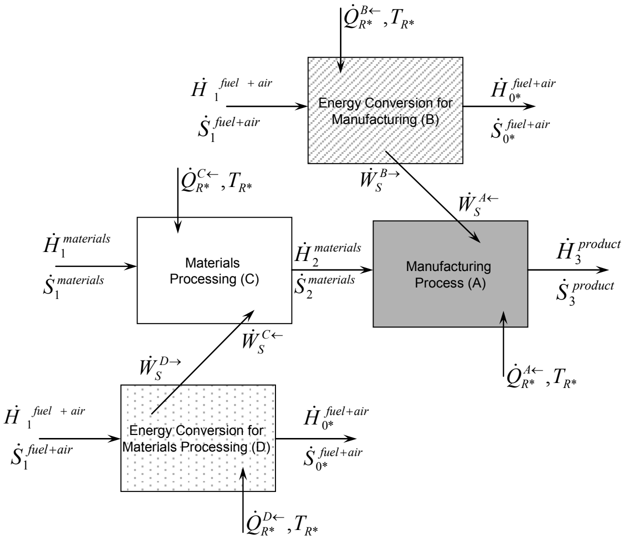


Figure 1: Overview of the thermodynamics of manufacturing processes (adapted from [1])

MANUFACTURING PROCESS LITERATURE

In this paper we draw heavily upon previous work in the area of manufacturing process characterization and compliment it with some of our own studies. In all we analyze 12 different manufacturing processes often in many different instances for each process. The key references are: in micro-electronics Murphy [5], Williams [6], Krishnan [7], and Zhang and Dornfeld [8]; in nano-materials processing, Isaacs [9]; in other manufacturing processes, Morow and Skerlos [10], Boustead [10, 11], Munoz and Sheng [13], Mattis and Sheng [14] and then some of our own works including Dahmus [15], Dalquist [16, 17], Thiriez [18, 19], Baniszewski [20], Kurd [21], Cho [22], Kordonowy [23], Jones [24] and Branham [25].

ENERGY REQUIREMENTS FOR THE MATERIALS USED IN MANUFACTURING PROCESSES

The energy required to produce a kilogram of input material for a manufacturing process depends upon the nature of the input materials, the quality requirements, and the technology employed. Furthermore as the technology improves with time this energy requirement decreases. Alternatively, as the required purity of the material increases, the energy requirement increases. This energy requirement is important because manufacturing processes differ widely in the efficiency of their material use. As a consequence the loss of energy intensive materials could be just as important, or even more important, than the direct energy requirements of the manufacturing process per se.

In Figure 2 the approximate electrical energy requirements for five materials are given. These inputs would correspond to $\dot{W}_S^{C\leftarrow}$ (in Figure 1) integrated over the time it takes to make one kilogram of material. The first, electric arc furnace steel is lowest because the quality of the input (mostly recycled steel) closely matches the quality requirements of the output. Aluminium is larger in part because of the requirements to break the strong $A1_2O_3$ bonds. The two silicon entries are large due to the high purity required [6] and the single wall carbon nanotube (SWNT) is very large due to the vapor processes used, the low yields, and the newness of the technology [9]. We can expect the nanotube energy to come down significantly, but even so, the trend is clear, large scale production of SWNTs would be very energy intensive.

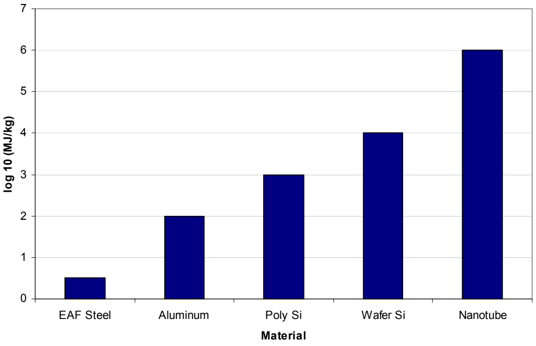


Figure 2. Electrical energy requirements for five materials.

ELECTRICAL ENERGY REQUIREMENTS FOR MANUFACTURING PROCESSES

Manufacturing processes are made up of a series of processing steps, which for high production situations are usually automated. For some manufacturing processes many steps can be integrated into a single piece of equipment. A modern milling machine, for example, can include a wide variety of functions including work handling, lubrication, chip removal, tool changing, and tool break detection, all in addition to the basic function of the machine tool, which is to cut metal by plastic deformation. The result is that these additional functions can often dominate energy requirements. This is shown in Figure 3 for an automotive machining line [26]. In this case, the maximum energy requirement for the actual machining is only 14.8% of the total. At lower production rates the machining contribution is even smaller. Other processes exhibit this same behaviour. See for example data for microelectronics fabrication processes as provided by Murphy [5]. Thiriez shows the same effect for injection molding [18, 19]. In general, there is a significant energy requirement to start-up and maintain the equipment in a "ready" position. Once in the "ready" position, there is then an additional requirement which is proportional to the quantity of material being processed. This situation is modelled in Equation 1.

$$P = P_o + k\dot{m} \qquad (1)$$

where P = total power, in W
P_o = idle power, in W
$\dot{m}$ = the rate of material processing in g/s, and
k = a constant, with units of J/g.

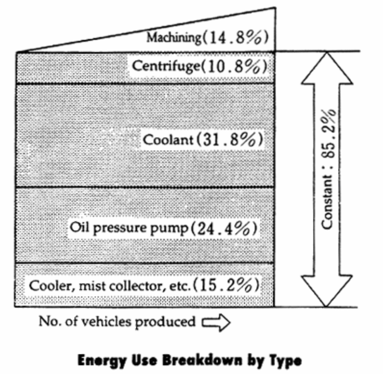


Figure 3: Energy used as a function of production rate for an automobile production machining line [26].

The specific electrical energy per unit of material processed, E_{elect}, in units of J/g, is then

$$E_{elect} = \frac{P_o}{\dot{m}} + k \qquad (2)$$

This corresponds to $\dot{W}_S^{A\leftarrow}$ (in Figure 1) integrated over the time it takes to process one unit mass of material. In general, the term P_o comes from the equipment features required to support the process, while k comes from the physics of the process. For example, for a cutting tool P_o comes from the coolant pump, hydraulic pump, computer console and other idling equipment, while k is the specific cutting energy which is closely related to the work piece hardness, the specifics of the cutting mechanics, and the spindle motor efficiency. For a thermal process, P_o comes from the power required to maintain the furnace at the proper temperature, while k is related to the incremental heat required to raise the temperature of a unit of production, this is related to the material heat capacity, temperature and the enthalpies of any phase changes that might take place.

One important point from this generalization is that the specific energy of a manufacturing process may be a strong function of throughput. Unlike the estimates often made in Life Cycle Assessment (LCA) software, specific process energy is not a constant, and can vary substantially particularly when operating at less than full capacity.

A second observation is that since the electrical power requirements of many manufacturing processes are actually quite constrained, while the process rates may vary by orders of magnitude, it might be possible to collapse their energy requirements data versus process rate, on a single log – log plot. This is shown in Figure 4 for 12 different manufacturing processes. Eleven of the 12 have maximum electrical power requirements between 5 and 50 kW, while their material processing rates cover 11 orders of magnitude. The figure shows that in spite of their constrained power requirements, their energy requirements per kg of material processed vary by seven orders of magnitude. This behavior is described by the first term on the right hand side of equation 2. At about 10 kg/hr there is a transition to a more constant energy requirement, essentially between 1 – 10 MJ/kg. This group includes electric induction melters with power requirements that far exceed the others, and with very high process rates. The data for this figure and their references are given in Table 1.

Note that an individual process can move up in electricity requirement by operating at a lower process rate. This happens, for example, when a milling machine is used for finish machining versus rough machining, or when a CVD process operates on 1 wafer versus 250 wafers at a time.

Note also that the data in Figure 4 may require further modification in order to agree with typical estimates of energy consumption by manufacturing processes given in the literature. For example, the data for injection molding, given by Thiriez, averages about 3 MJ/kg. At a grid efficiency of 33%, this yields a specific energy value of 10 MJ/kg. However, most injection molding operations include a variety of additional sub-processes such as extrusion, compounding, and drying, all of which add substantially to the energy totals. If these additional pieces of equipment are also included, they result in a value for injection molding of about 20 MJ/kg which agrees with the literature [12-13,18].

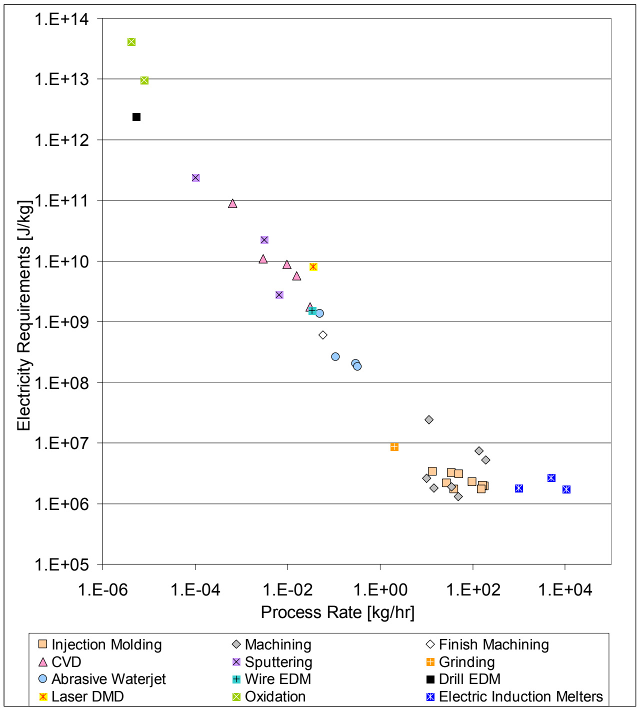


Figure 4: Specific electricity requirements for various manufacturing processes as a function of the rate of materials processed.

The data in Figure 4 can also be viewed in a historical sense. In general, the processes in the lower right hand corner of the figure are older, more conventional processes, while those in the upper left hand corner are newer microelectronics and advanced machining processes. These more modern processes can work to finer dimensions and smaller scales, but also work at lower rates, resulting in very large specific electrical energy requirements. In short, the historical trend is clearly towards more energy-intensive manufacturing processes.

	Estimates				
Process Name	**Power Required**	**Process Rate**	**Electricity Required**	**Note**	**Refer-ences**
	kW	**kg/hr**	**J/kg**		
Injection Molding	10.76	1.36E+01	3.39E+06	----	[18]
	26.10	3.54E+01	3.19E+06	----	
	71.40	1.83E+02	1.94E+06	----	
	35.76	5.08E+01	3.07E+06	----	
	47.46	9.80E+01	2.28E+06	----	
	65.34	1.63E+02	1.98E+06	----	
	12.73	2.77E+01	2.19E+06	----	
	13.17	3.95E+01	1.74E+06	----	
	51.41	1.54E+02	1.74E+06	----	
Machining	194.80	1.94E+02	5.26E+06	----	[15]
	194.80	1.35E+02	7.50E+06	----	
	10.65	4.86E+01	1.30E+06	----	[15]
	10.65	3.46E+01	1.88E+06	----	
	2.80	1.46E+01	1.81E+06	----	[15]
	2.80	1.01E+01	2.63E+06	----	
	75.16	1.13E+01	2.40E+07	a	[29,30]
Finish Machining	9.59	5.75E-02	6.00E+08	a	[29,30]
CVD	16.00	6.36E-04	9.05E+10	----	[5]
	6.75	2.96E-03	1.10E+10	b	[39]
	15.00	3.09E-02	1.75E+09	b	[31]
	14.78	9.48E-03	8.89E+09	b	[32]
	25.00	1.57E-02	5.72E+09	d	[33]
Sputtering	6.75	1.02E-04	2.39E+11	b	[31]
	19.50	3.16E-03	2.22E+10	b	
	5.04	6.51E-03	2.79E+09	----	[31, 34]
Grinding	10.00	4.70E-01	8.79E+06	----	[20]
Waterjet	16.00	2.93E-01	2.03E+08	----	[21]
	0.00	3.27E-01	1.82E+08	----	
	8.16	1.11E-01	2.65E+08	a	[21]
	8.16	5.01E-02	1.36E+09	a	[21]
Wire EDM	14.25	3.34E-02	1.54E+09	----	[28, 35]
Drill EDM	2.63	5.29E-06	2.38E+12	b	[36,37]
Laser DMD	80.00	3.60E-02	8.00E+09	b	[29]
Oxidation	21.00	7.80E-06	9.69E+12	d	[5]
	48.00	4.16E-06	4.15E+13	d	[5]
Electric Induction Melting	5000.00	1.05E+04	1.72E+06	----	[24]
	500.00	9.98E+02	1.80E+06	----	[24]
	3750.00	4.99E+03	2.71E+06	----	[24]

Notes/Assumptions:

a = Required power is back-calculated from SEC (in MJ/kg or J/cm^3) and throughput (cm^3/s).

b = Power required is assumed to be 75% of rated power.

c = Power required is equal to rated power since the machine is operating at maximum throughput.

d = If both idle and run power are provided, the machine is assumed to run 100% of the time with the exception of machining.

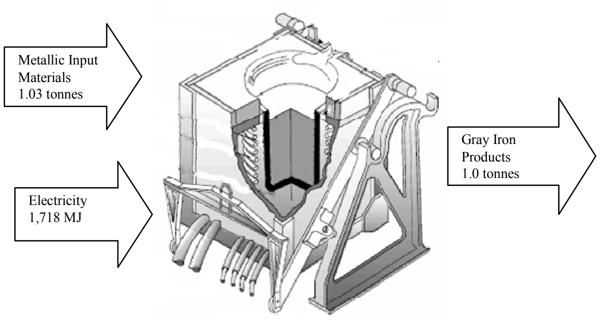
Table 1. Data for Figure 4.

MATERIAL & ENERGY EFFICIENCY IN MANUFACTURING PROCESSES

The previous sections showed the increased energy requirements for high purity materials processed at slow rates into micro and nano scale features and devices. Here we illustrate the dramatic reduction in efficiency that accompanies these changes using the so called "degree of perfection", Szargut [4].

$$\eta_p = \frac{B_{useful\_products}}{B_{inputs}} \tag{3}$$

The numerator represents the material exergy of the useful output product produced by the manufacturing process. The denominator represents the exergy of the input materials and electricity into the process. Here we will illustrate this calculation for two manufacturing processes at opposite ends of the material throughput spectrum. At the high production rate end, we analyze a batch electric induction melter (see Figure 5) as used in the iron foundry industry. And at the low production rate we look at plasma-enhanced chemical vapor deposition of undoped silicate glass as used in the semi-conductor industry. The materials and electricity exergy data and the results are given in Tables 2 and 3 respectively. We see that the efficiencies differ by about 6 orders of magnitude. Note that this analysis uses only the direct inputs and outputs as illustrated by the A "box" in Figure 1. Future work will look at larger boundaries. The data below can also be used to calculate the mass ratio of materials in, to product out. This value for electric induction melting is about 1.03 to 1, while for the CVD process the ratio is over 10,000 to 1.



Boundaries are drawn around the entire facility so that all components are at standard pressure and temperature

Figure 5: Inputs and Useful Outputs for Batch Electric Induction Melting [24, 41]

	Exergy Input	
Material	Exergy, B	Percent of Total Input
Scrap Metallics	6,200 MJ	59.5%
Cast Iron Remelt	2,500 MJ	24%
Electricity	1,720 MJ	16.5%
Totals B_{inputs}	**10,420 MJ**	**100%**
	Exergy Useful Products	
Material	Exergy, B	Percent of Total Output
Gray Iron Melt	8,250 MJ	99%
Totals $B_{useful\_products}$	8,250 MJ	
Total Exergy Loss, $B_{waste}+B_{lost}$	2,170 MJ	
Degree of Perfection,	**0.79**	

Table 2: Data for Batch Electric Induction Melting (One tonne melt) [24]

Input Deposition Gases			
Gas	*Input moles or energy*	*Exergy (J)*	*%Total*
SiH4	0.029579 mol	40,928.6	0.749%
O2	0.015313 mol	60.79	
Ar	0.008511 mol	99.49	
N2	7.028779 mol	4,849.9	
Input Cleaning Gases			
CH4	4.326643 mol	3,598,253	63.0%
NF3	0.437453 mol	266,931.6	
Input Energy			
Electricity	2,220,000 J	2,220,000	36.2 %
Useful Outputs			
Undoped Silicate Glass layer	0.000414 mol	3.267	100%
Degree of Perfection	**$5.33*10^{-7}$**		

Table 3: Data for Plasma-Enhanced Chemical Vapor Deposition (PECVD) of a single wafer [25]

SUMMARY

In this paper we summarize trends on how energy and materials are used in manufacturing processes. These trends do not give the whole story for any given application. New manufacturing processes can provide benefits to society and even to the environment by providing longer life and /or lower energy required in the use phase of products or in any number of performance benefits. Nevertheless, the seemingly extravagant use of materials and energy by many newer manufacturing processes is alarming and would not be sustainable in an era of much higher energy costs and potential carbon taxes. The purpose of this paper is to highlight these liabilities and to prompt their inclusion in the agenda for new process and product development.

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