Article

Thermodynamic Analysis of Resources Used in Thermal Spray Processes: Energy and Exergy Methods

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Abstract: In manufacturing, thermal spray technology encompasses a group of coating processes that provide functional surfaces to improve the performance of the components and protect them from corrosion, wear, heat and other failings. Many types and forms of feedstock can be thermal sprayed, and each requires different process conditions and life cycle preparations. The required thermal energy is generated by a chemical (combustion) or electrical (plasma/or arc) energy source. Due to high inefficiencies associated with energy and material consumption in this process, a comprehensive resources used analysis for a sustainable improvement has always been promising. This study aims to identify and compare the influence of using different forms of feedstock (powder, suspension) as well as energy sources (combustion, plasma) on efficiency and effectiveness of energy conversion and resources consumption for different thermal spray processes based on energy and exergy analysis. Exergy destruction ratio and effectiveness efficiency are used to evaluate the energy conversion efficiency. The degree of perfection and degree of energy ratio are applied to account for the intensity of resources consumption (energy or material) in thermal spray processes. It is indicated that high velocity suspension flame spray has the lowest effectiveness efficiency and the highest exergy destruction compared to other thermal spray processes. For resource accounting purposes, in general, suspension thermal spray showed the lower degree of perfection and accordingly the higher inefficiency of resources used compared to powder thermal spray.

Keywords: energy; exergy; effectiveness efficiency; thermal spray; resources

1. Introduction

The main purpose in manufacturing is to transform raw materials into useful products. The seemingly extravagant use of processing and auxiliary materials as well as energy by many newer manufacturing processes is alarming and needed to be addressed alongside claims of improving sustainability [1]. Thermal spray process is an energy and resource intensive manufacturing process in which thermal energy is generated from electrical plasma/arc or fuel combustion. These energy sources are used to heat the coating material (for example, powder and suspension) to a molten state. The resultant heated particles are accelerated and propelled toward the workpiece by either process gases or atomization jets. Inefficiency of the process in coating deposition as well as energy conversion can have significant effects on environment and sustainable use of resources [2]. Thermodynamics is introduced as a well-suited method to analyze the magnitude of these effects as well as the efficiency of the energy transformation [3,4].

To manufacture diverse coating quality, different types of feedstock (such as powder and suspension) can be applied in thermal spray [5–7]. However, the question has been raised regarding the impact of using different forms of feedstock on energy conversion efficiency and intensity of resource consumption in accordance with the type and characteristics of the applied thermal spray technique. In this work, atmospheric plasma spray (APS), suspension plasma spray (SPS), high velocity oxy-fuel spray (HVOF) and high velocity suspension flame spray (HVSFS) are investigated. Thermodynamic methods are applied for process evaluation and resource accounting. The analysis approach includes:

- process effectiveness efficiency and exergy destruction analysis to measure process performance in energy conversion and deviation from optimal condition;
- resources used analysis to identify and allocate the intensity consumption of resources (energy or material).

The general overview of the advantages of using exergy analysis in comparison with conventional energy analysis for evaluation of thermal spray process inefficiencies was discussed [8]. However, this study provides a detailed useful insight into various exergy-based methods to highlight the inefficient use of resources, with an emphasis on both process evaluation and resource accounting. It is underlined that integration of the results of energy conversion efficiency and resource accounting provides a framework for identifying, comparing and prevention of the inefficiencies associated with the resources used.

For exergy efficiency and exergy destruction analysis, the spray torch was considered as the analysis boundary where the input energy is converted to the heat for melting/vaporizing of the powder/suspension feedstock. For the effectiveness efficiency and resource accounting, the analysis boundary was extended to the coating as the useful product.

2. Analysis Methodologies

Exergy analysis of thermal system has been practiced by many authors [9–12]. Exergy methods provide complementary useful information to conventional energy assessments. In general, performance of the manufacturing systems can be described in thermodynamic terms by formulating energy, mass and exergy balance. For the thermal spray process, energy in the form of electrical plasma or fuel combustion is converted to heat, which is partly removed as the heat loss by the process cooling. Then, the useful heat is transferred to the gas mixture of the flame/plasma down the nozzle jet to melt and accelerate the feedstock on to the surface of the workpiece. The energy and exergy balance of the thermal spray torch are as follows.

2.1. Energy Balance

The general energy balance of the torch in thermal spray can be written as:

$$\text{Energy input} - \text{Heat loss to the cooling water} = \text{Heat output} \tag{1}$$

$$\dot{W}_F - \dot{Q}_l = \dot{Q}_{out} \tag{2}$$

where $\dot{W}_F$, $\dot{Q}_l$ and $\dot{Q}_{out}$ are the input energy, heat loss and heat output rate, respectively. Cooling water is required to increase the lifetime of the torch [2]. It is assumed that the net conductive, radiative and electrode heat losses of the torch are removed by the cooling water and can be evaluated as below:

$$\dot{Q}_l = \dot{m}_w c_w \Delta T \tag{3}$$

where, $\dot{m}_w$ and c_w are the mass flow rate and specific heat at constant pressure of the water, and ΔT is the temperature difference between inlet-outlet temperatures of the water circuit. Hence, the thermal (energy) efficiency of the torch becomes:

$$\eta_{en} = \frac{\dot{Q}_{out}}{\dot{W}_F} \tag{4}$$

2.2. Exergy Balance

Considering the spray torch as an analysis boundary, Figure 1 shows schematically the input–output exergy flows of the torch.
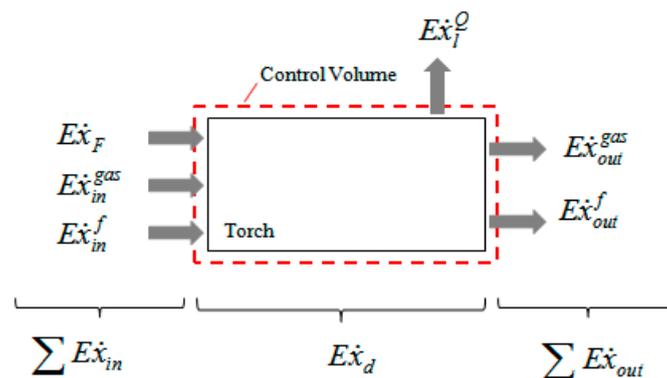
Figure 1. Exergy balance for thermal spray torch boundary.

From the exergy balance in Figure 1, $\sum \dot{Ex}_{in}$, $\sum \dot{Ex}_{out}$, $\dot{Ex}_d$ are the total exergy input, output and destruction rate, respectively. Specifically, $\dot{Ex}_F$, $\dot{Ex}_{in}^{gas}$ and $\dot{Ex}_{in}^{f}$ are the input energy, gas mixture and feedstock exergy rates. $\dot{Ex}_{out}^{f}$ and $\dot{Ex}_{out}^{gas}$ are the feedstock and gas mixture exergy rates in the outlet jet. $\dot{Ex}_{l}^{Q}$ is the exergy rate of the total heat loss. The general exergy balance for the thermal spray torch can be written as follows:

$$\text{Exergy input} - \text{Exergy of heat loss to the cooling water} - \text{Exergy destruction} = \text{Exergy output} \tag{5}$$

For each single gas/feedstock stream of the jet, the steady-state exergy rate balance is as Equation (6). Depending on type of thermal spray process, the outlet jet may consist of process gases, combustion products and feedstock. Here, the total exergy associated with a specific state of a flow is the sum of thermomechanical/physical and chemical exergy. By definition, physical exergy is the work obtainable by taking the substance through reversible physical processes from its specific state (T, p) to the atmospheric state (T_0, p_0). Chemical exergy is the work that can be obtained when the considered substance is brought into reaction with reference substances present in the environment. In evaluating chemical exergy, besides temperature and pressure, the difference in a system and environment's chemical composition is also taken into account [11]. Since the temperature of the gases changes significantly by passing through the torch, the assumption of constant specific heats might lead to considerable errors in entropy change calculation. Therefore, the entropy of each gas is determined for each specific state (T, p) [12]:

$$\dot{Ex} = \dot{m}[h(T) - h(T_0) - T_0(s(T) - s(T_0)) + e^{ch} + \frac{v^2}{2}] \tag{6}$$

where $\dot{m}, h, s, e^{ch}, v$ are the mass flow rate, specific enthalpy and entropy, chemical exergy and velocity of a component. The outlet axial velocity of each stream is assumed to be the same as the axial velocity or speed of the nozzle jet exit. The ideal gas model can be applied for the gas streams since they are at

the high temperature and low pressure relative to their critical point [13]. Therefore, Equation (6) is written as:

$$E\dot{x} = \dot{m}[h(T) - h(T_0) - T_0(s(T) - s(T_0) - \text{Rln}\frac{p}{p_0}) + e^{ch} + \frac{v^2}{2}] \tag{7}$$

For the process combined with combustion reaction, the flow exergy of each reaction component is calculated as below [14]:

$$E\dot{x} = \dot{m}(n_i[\overline{h}_f^0 + \overline{h}(T) - \overline{h}(T_0) - T_0(\overline{s}(T) - \overline{s}(T_0) - \overline{R}\text{ln}(\frac{y_i p}{y_i p_o})) + e^{ch}] + \frac{v^2}{2}) \tag{8}$$

where n_i, y_i, $\overline{h}_f^0$ and $\overline{h}$ denote, respectively, the number of mole and mole fraction of compound (*i*), standard enthalpy of formation and enthalpy per mole. When a difference in exergy or flow exergy between states of the same composition is evaluated, the chemical contribution of exergy is canceled, leaving just the difference in the thermomechanical contributions. For such a calculation, it is unnecessary to evaluate the chemical exergy explicitly. Hence, the net exergy destruction can be evaluated from the overall exergy balance of the torch as a control volume in a steady-state condition, as it is expressed in Equation (9). Furthermore, for the combustion reaction at high temperature, chemical exergy contribution to the flow exergy is relatively small and can also be neglected [13]. In the flame spray, both feedstock and carrier gas are passing through the torch, and thus the exergy change of the feedstock is also taken into account:

$$0 = E\dot{x}_F - E\dot{x}_l^Q + E\dot{x}_{in}^{gas} - E\dot{x}_{out}^{gas} + E\dot{x}_{in}^f - E\dot{x}_{out}^f - E\dot{x}_d \tag{9}$$

In the thermal spray process, the heat is generated from the input energy source (electricity or fuel combustion) at T_F with an exergy ate of $\left(1 - \frac{T_0}{T_F}\right)\dot{Q}_F$. According to Figure 2, T_F for plasma and flame spray is the plasma jet temperature and adiabatic flame temperature, respectively. The rate of exergy transfer accompanying heat loss at T_l is $\left(1 - \frac{T_0}{T_l}\right)\dot{Q}_l$. T_l is assumed as the outlet cooling water temperature on the outer surface of the torch, which continuously removes the heat loss. The useful heat is transferred out by the gases and feedstock mixture from the nozzle jet. Accordingly, the exergy efficiency of the torch is evaluated from the thermomechanical exergy of the input–output streams:

$$\psi_{torch} = \frac{E\dot{x}_{out}}{E\dot{x}_F} = 1 - \frac{E\dot{x}_d + E\dot{x}_l^Q}{E\dot{x}_F} \tag{10}$$

Torch zone parameters	(1)	(2)	(3)	(4)
Pressure (bar)	6	2	1	1
Temperature (K)	293	12000	10000	4000

Torch zone parameters	(1)	(2)	(3)	(4)
Pressure (bar)	6	3	1	1
Temperature (K)	293	2900	2700	900

(a)　　　　　　　　　　　　　　　　　　　　　　(b)
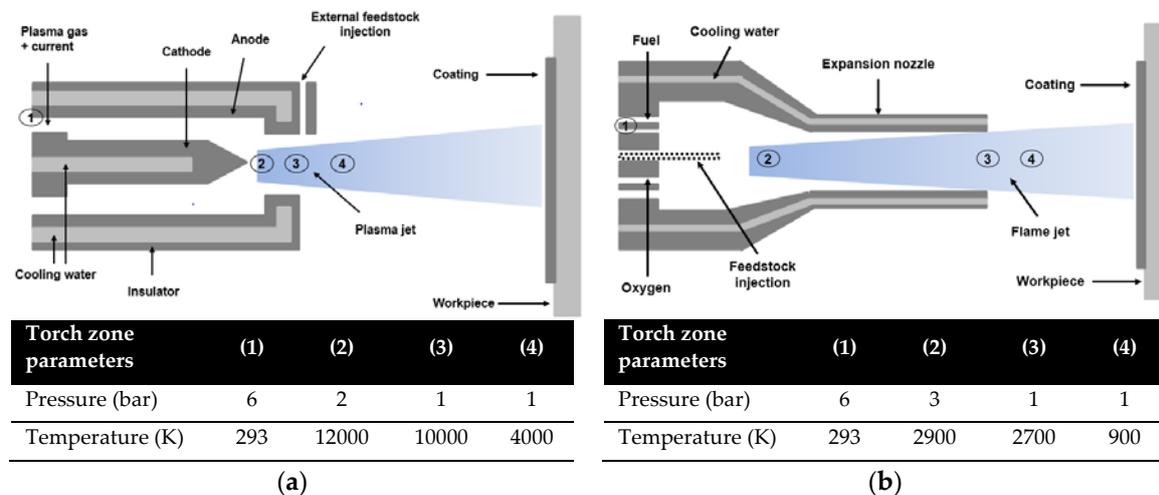
Figure 2. Schematic of (**a**) plasma and; (**b**) flame thermal spray [15].

Knowing the total exergy destruction of the torch, energy conversion inefficiencies can be compared by exergy destruction and exergy destruction ratio, as it is expressed in Equation (11):

$$y_x = \frac{E\dot{x}_d}{E\dot{x}_F} \tag{11}$$

Effectiveness or task efficiency is defined as a measurement of exergy efficiency. It is simply describing how well a process utilizes energy to convert the raw materials into products. It provides a general realistic measure of the degree to which the performance of a process can be improved [1,16]. Effectiveness efficiency [1] is defined as the ratio of the theoretical minimum required exergy to perform a task (such as manufacturing coating) to the actual energy or exergy used as Equation (12):

$$\varepsilon = \frac{\dot{W}_{min}}{\dot{W}_{actual}} \tag{12}$$

For the thermal spray process, the theoretical minimum required exergy is equivalent to the minimum needed exergy for melting, vaporizing and accelerating feedstock onto the workpiece. Depending on the type of process, it is calculated as below:

$$\dot{W}_{min} = \dot{m}_P[(1 - \frac{T_0}{T_m})\Delta h_m + \frac{v_P^2}{2}] + \dot{m}_s \Delta h_{s,V} \tag{13}$$

where $\dot{m}_P$ $\dot{m}_s$ v_P are the mass flow rate of the powder and solvent (such as isopropanol) and the powder velocity. Referring to Equation (14), degree of perfection was introduced for resource accounting and evaluation of resources used intensity [11]. For manufacturing processes, it can be defined as the ratio of chemical exergy of the useful output product (for example, the chemical exergy of the manufactured coating) to the sum of the exergy inputs including the exergy of any work and/or heat inputs as well as chemical exergy of all input materials [4,11]. In manufacturing, auxiliary materials are used, which will then not appear in the end products. However, due to their preparation and purification, some might have very high chemical exergy, which is destroyed during a process [4]:

$$\eta_p = \frac{Ex_{out}}{\sum Ex_{in}} \tag{14}$$

This accounting applies equally to all participating energy and materials with the same unit (kJ). Therefore, inefficiency of a process in resource consumption can be addressed specifically to energy or material used [4]. To allocate the resources consumption specifically to energy and materials, the degree of energy ratio is defined, which provides useful information for focusing on energy or material reduction for further sustainable resources use effectiveness. According to Equation (15), the degree of energy ratio is defined as the ratio of exergy of input energy to the total input exergy:

$$X_F = \frac{Ex_F}{\sum Ex_{in}} \tag{15}$$

3. Results and Discussion

3.1. Experimental Data

For the analyzed thermal spay processes, the heat is produced, respectively, from the electrical plasma and the fuel combustion in plasma and flame thermal spray. The heat is transferred to the gas mixture under high pressure and temperature that accelerates the resulting flame/gas stream down a nozzle jet [2]. In this study, the functional unit for the comparison was the spray duration (approximately 9 seconds). The powder and solvent were aluminum oxide (Al_2O_3) and isopropanol (C_3H_8O). Feedstock flow rate for powder thermal spray (100 wt% powder) and for suspension thermal

spray (20 wt% powder) was approx. 46.5 g/min and 57.2 g/min, respectively. The melting enthalpy of aluminum oxide and enthalpy of vaporization of isopropanol (C_3H_8O) were 1.54 kJ/g and 0.73 kJ/g. In HVOF and HVSFS, feedstock (powder/suspension) and the carrier gas (nitrogen) were axially entered into the torch. On the other hand, the feedstock was injected radial at the torch outlet in APS and SPS. The process parameters are summarized in Table 1. The gas flow rate (g/s) was calculated from the given flow rate (L/min) and the gas density.

Table 1. Plasma and flame thermal spray parameters for Al_2O_3 coating.

Parameters	APS	SPS	HVOF	HVSFS	Unit
Ar	39	39	–	–	L/min
N_2	7	7	25	–	L/min
H_2	9	9	–	–	L/min
O_2	–	–	320	320	L/min
C_2H_4	–	–	90	90	L/min
Current	550	550	–	–	A
Power	39	39	–	–	kW
Cooling power	19.2	19.2	12.6	12.6	kW
Water flow rate	13.5	13.5	28.8	28.8	L/min
Inlet water temperature	18.5	18.5	23.7	23.7	°C
Outlet water temperature	39	39	30	30	°C
Feedstock	Al_2O_3 Powder	20 wt% Al_2O_3 in isopropanol	Al_2O_3 Powder	20 wt% Al_2O_3 in isopropanol	–
Al_2O_3	46.6	11.6	46.6	11.6	g/min
C_3H_8O	–	45.6	–	45.6	g/min
Nozzle jet axial velocity [2,15]	600	600	1200	1200	m/s

3.2. Effectiveness Analysis

For exergetic analysis of the process, it was assumed that the exergy of the input energy (electricity, fuel) was equivalent to its energy value. Figure 2 shows the physical conditions of the torch. The entrance torch pressure was measured from the gas container pressure and the exit pressure was the atmospheric pressure. Inlet temperature was assumed as atmospheric temperature. Pressures and temperatures inside the torch and the torch outlet are well defined in the literature [2,15].

As demonstrated in Figure 3, with an assumption of steady-state condition, specific enthalpy and entropy change of the gas mixture are schematically illustrated in an enthalpy–entropy (h–s) diagram. Generally, due to the high temperature in plasma, the specific enthalpy is higher compared to flame spray [2]. However, considering the same spray duration as the function unit in this work, the input enthalpy of the flame spray was higher than plasma spray. It is observed that the enthalpy of gas mixture is increased (0–1). In flame spray, there is a reduction of enthalpy and an increase of entropy as the temperature and pressure are reduced from combustion chamber to the nozzle jet (1′–1). The heat loss is removed at the constant pressure of the torch (1–2). Enthalpy decreases as the gas mixture leaves the torch (2–3). The total output gas enthalpy is the sum of thermal and kinetic energy of gases in plasma/flame jet. However, the kinetic energy is relatively small compared to the thermal energy of the jet, especially for the case of plasma spray [2,15].

Also the results from entropy change are used for calculation of the physical exergy destruction. It is shown that the entropy generation of the flame thermal spray is higher than of the plasma spray because of the additional irreversibility associated with energy conversion of the combustion, which converts a fuel and oxygen stream into the products of combustion.

Knowing the theoretical minimum exergy from Equation (13) and the actual consumed exergy in Table 1, effectiveness efficiency was calculated by Equation (12). Theoretical minimum required exergy was evaluated by the given parameters in Table 1, melting enthalpy of alumina and vaporization enthalpy of the isopropanol. The results are compared for thermal spray processes in Figure 4.
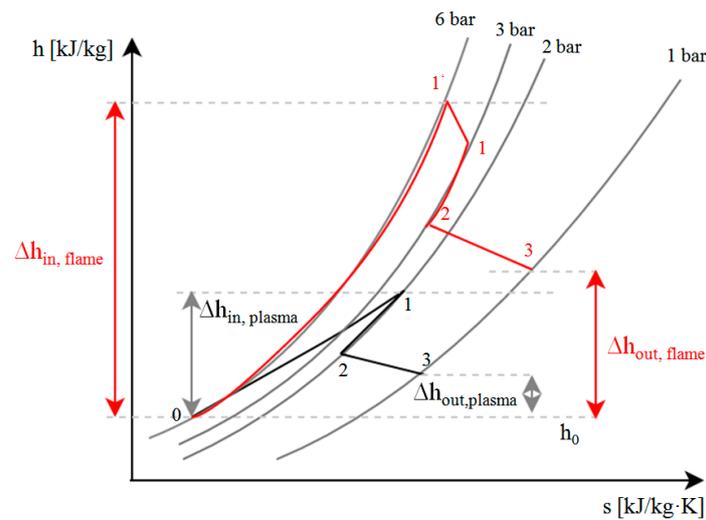
Figure 3. Specific enthalpy and entropy comparison of plasma and flame thermal spray in enthalpy–entropy (h–s) diagram for the same spray duration.
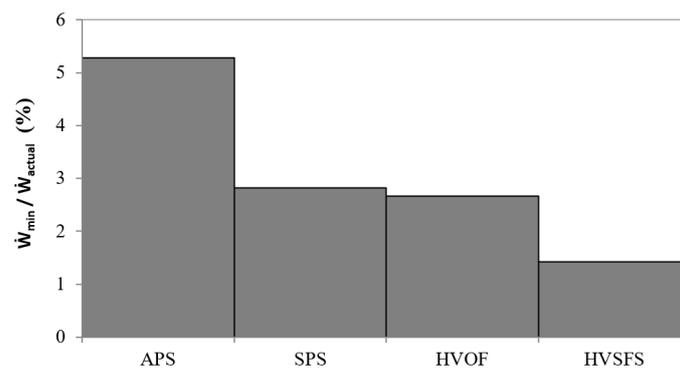
Figure 4. Comparison of effectiveness efficiency for thermal spray processes.

Effectiveness efficiency measures the process performance in doing a task encompassing the efficiency of the energy and material use. It was observed that flame thermal spray in general had the lower effectiveness efficiency compared to plasma spray. Furthermore, because of the lower vaporization energy of C_3H_8O than melting energy of Al_2O_3, required minimum theoretical exergy for the suspension feedstock was lower compared to 100 wt% powder feedstock.

The given parameters in Table 1, Figures 2 and 3 were applied for the torch energy and exergy balances. From the energy analysis, Equations (1) to (4), it can be seen that the thermal efficiency of the flame spray was much higher than the plasma spray, which is interpreted by the lower torch temperature and respective conductive and radiative heat losses. However, comparison of thermal spray processes based on only thermal efficiency did not give concrete information about the effectiveness of the energy conversion. Therefore, exergy-based methods, Equations (5) to (11), were also carried out for evaluation of the energy conversion efficiency in accordance with entropy generation. The results were calculated based on thermomechanical/physical exergy of the torch. From the exergy analysis, exergy destruction rate contributed as the major inefficiencies followed by exergy rate of heat loss, while the heat losses were considered as the total inefficiencies from the energy analysis. The results are summarized in Table 2.

Table 2. Energy and exergy balances for the thermal spray torch.

Spray Process	$\dot{En}_F$ (kW)	$\dot{En}_l^Q$ (kW)	$\dot{En}_{out}$ (kW)	$\dot{Ex}_F$ (kW)	$\dot{Ex}_l^Q$ (kW)	$\dot{Ex}_d$ (kW)	$\dot{Ex}_{out}$ (kW)	η (%)	Ψ (%)
APS	39	19.2	19.8	37.8	1.17	23.5	13.1	50.8	34.6
SPS	39	19.2	19.8	37.8	1.17	23.5	13.1	50.8	34.6
HVOF	84	12.6	71.4	74.9	0.81	35.5	38.6	85	51.5
HVSFS	84	12.6	71.4	74.9	0.81	37.7	36.4	85	48.6

As it was expected, exergy destruction associated with flame spray was higher than that of plasma spray due to the irreversibilities of the combustion and change in gas compositions. However, as the exergy input for the flame spray was higher than plasma spray for the same spray duration, its exergy destruction ratio was lower compared to plasma spray, see Figure 5.
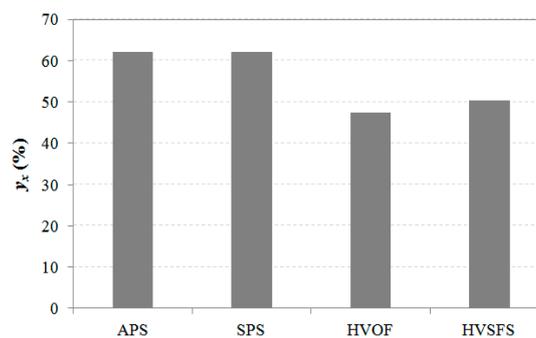
Figure 5. Comparison of exergy destruction ratio for thermal spray processes.

It can be concluded that suspension flame spray in general had the highest destruction of the input exergy or the worst effectiveness of the energy conversion.

3.3. Resource Accounting

According to the definition of the degree of perfection, the chemical exergy of the energy and material streams need to be taken into account. Chemical exergy of the participating components are given in literature [11] and listed in Table 3. As represented in Table 4, exergy of each stream was obtained from the chemical exergy and the quantity of each stream. The quantities of streams were calculated from the process parameters given in Table 1 and spray duration. Note that the exergy of the Al_2O_3 coating was considered as the useful output exergy. The very low value of degree of perfection showed the high amount of input resources (energy, materials) was consumed inefficiently and lost. Due to vaporization and loss of C_3H_8O as an auxiliary material, the degree of perfection for suspension thermal spray was lower than that of powder thermal spray.

Table 3. Chemical exergy of the applied materials in thermal spray.

Materials	Molar mass (g/mol)	Chemical exergy (*ex*) (kJ/mol)
Al_2O_3	101.9	200
Ar	39.9	11.7
N_2	28	0.72
H_2	2	236.1
O_2	32	4
C_2H_4	28	1361
C_3H_8O	60	1998.6

Table 4. Input–output exergy and degree of perfection of thermal spray Al_2O_3 coating; functional unit: spray duration.

Streams	APS		SPS		HVOF		HVSFS	
	m (g)	*Exergy* (kJ)	*m* (g)	*Exergy* (kJ)	*m* (g)	*Exergy* (kJ)	*m* (g)	*Exergy* (kJ)
Input materials								
Al_2O_3	6.33	12.4	1.58	3.1	6.33	12.4	1.58	3.1
Ar	9.66	2.8	9.66	2.8	–	–	–	–
N_2	1.21	0.03	1.21	0.03	4.3	0.1	4.3	0.1
H_2	0.11	13.3	0.11	13.3	–	–	–	–
O_2	–	–	–	–	63.5	7.9	63.5	7.9
C_2H_4	–	–	–	–	14.7	742	14.7	742
C_3H_8O	–	–	6.33	211	–	–	6.33	211
Input energy								
Electricity	–	325	–	325	–	–	–	–
Sum of inputs	–	353.5	–	555	–	762.4	–	965
Output								
Al_2O_3 coating	0.36	0.7	0.12	0.24	1.36	2.67	0.46	0.9
Degree of perfection (η_p)	2×10^{-3}		4.3×10^{-4}		3.5×10^{-3}		9.3×10^{-4}	

Furthermore, as it is shown in Figure 6, the lower degree of energy ratio of suspension compared to powder thermal spray underlines that suspension thermal spray was more associated with material loss than energy loss.
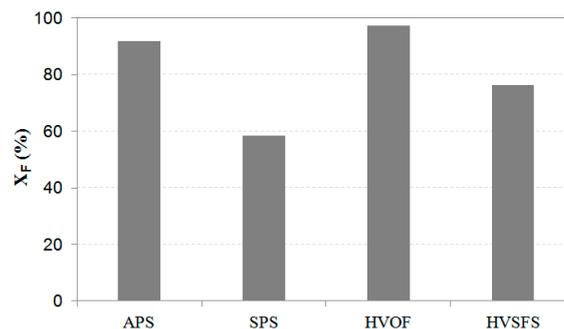
Figure 6. Comparison of degree of energy ratio for thermal spray processes.

4. Conclusions

Thermodynamic energy and exergy analysis were conducted to compare the efficiency and effectiveness of the energy conversion along with resources used evaluation in thermal spray processes. For the torch energy conversion efficiency analysis, it was pointed out that thermal efficiency was not a suitable indicator for the comparison of thermal spray processes as the cooling capacity for plasma and flame spray varied in accordance with each process characteristic.

Considering the same spray duration, flame spray showed the lower effectiveness efficiency compared to plasma spraying, which emphasized the higher inefficiency of the energy used. The big difference between the results of effectiveness efficiency and exergy efficiency was because of different analysis boundaries. For effectiveness efficiency evaluation, the analysis boundary was extended to the coated workpiece and, therefore, major energy and material losses occurred from the nozzle exit to the workpiece. The results of exergy destruction analysis highlighted the energy conversion inefficiency in the torch. It was indicated that the exergy destruction associated with flame spray was higher than that of plasma spray due to the combustion and change in gas compositions. Additionally, using suspension feedstock increased the exergy destruction.

From resource accounting, and according to the presented results in Table 4, the lower value of degree of perfection for suspension compared to powder thermal spray signified the participation and

loss of high exergetic auxiliary material (C_3H_8O) without appearing in the final manufactured coating. This result can also be seen in Figure 6 as the degree of energy ratio was lower for suspension thermal spray processes. For powder thermal spray processes, on the other hand, the biggest part of exergy losses was associated with inefficient energy utilization.

For resource saving and sustainable improvement of thermal manufacturing processes, the same approach can be used for comparison of different forms of feedstock, process techniques and auxiliary materials.

Author Contributions: Kamran Taheri as the first and corresponding author was responsible for the idea, analysis and writing of the paper. Mohamed Elhoriny and Martin Plachetta contributed in experimental and revision parts of the work; Rainer Gadow was the supervisor and the institute's director. All authors have read and approved the final manuscript.

Conflicts of Interest: The authors declare no conflict of interest.

Nomenclature

Ar	argon
C_2H_4	ethylene
C_3H_8O	isopropanol
$\dot{En}$	energy rate (kW)
$\dot{Ex}$	exergy rate (kW)
Ex	exergy (kJ)
ex	chemical exergy (kJ/mol)
h	specific enthalpy (kJ/g)
$\bar{h}$	molar enthalpy (kJ/mol)
$\bar{h}_f^0$	standard enthalpy of formation (kJ/mol)
H_2	hydrogen
$\dot{m}$	mass flow rate (g/s)
M	molar mass (g/mol)
O_2	oxygen
n	number of moles
N_2	nitrogen
p	pressure (bar)
$\bar{R}$	gas constant (J/mol·K)
s	specific entropy (kJ/kg·K)
S	entropy (kJ/K)
T	temperature (°C or K)
v	velocity (m/s)
$\dot{W}$	work rate (kW)
y_i	mole fraction
y_x	exergy destruction ratio (%)
Subscript	
0	ambient/atmospheric condition
F	input energy
d	destruction
en	energy
gen	generation
in	input stream

j	jet
l	loss
m	melt
min	minimum
mix	mixture
out	outlet stream
P	powder
s	solvent
v	vaporization
w	water

Superscript

ch	chemical exergy
f	feedstock
Q	heat

Greek letter

η	energy efficiency (%)
η_P	degree of perfection (%)
Ψ	exergy efficiency (%)
ε	effectiveness efficiency (%)
X_F	degree of energy ratio (%)

Abbreviations

APS	Atmospheric Plasma Spray
HVOF	High Velocity Oxy-Fuel Flame Spray
HVSFS	High Velocity Suspension Flame Spray
SPS	Suspension Plasma Spray

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