Available online at www.sciencedirect.com
ScienceDirect
Procedia CIRP 17 (2014) 511 – 516
www.elsevier.com/locate/procedia

Variety Management in Manufacturing. Proceedings of the 47th CIRP Conference on Manufacturing Systems

Exergy analysis as a developed concept of energy efficiency optimized processes: The case of thermal spray processes

Kamran Taheri[a], Rainer Gadow[a,b], Andreas Killinger[c]*

[a] *Graduate School of Excellence advanced Manufacturing Engineering (GSaME), 70569 Stuttgart, Germany*

[b,C] *Institut für Fertigungstechnologie keramischer Bauteile (IFKB), Allmandring 7b, 70569 Stuttgart, Germany*

* Corresponding author. Tel.: +49 71168568221; fax: +49 711 685-68299. E-*mail address:* kamran.taheri@gsame.uni-stuttgart.de

Abstract

Given the global economic growth and the rapid manufacturing development, the energy and resource efficiency will become an increasingly competitive factor and scope for the companies in the road of sustainability. Among energy efficiency optimization approaches, thermodynamics methodologies contribute toward the improvement of energy efficiency in manufacturing processes. Besides energy balance, exergy has been recently considered as a practical thermodynamics method for system's energy evaluation. From the exergy analysis, merging both exergy efficiency and exergy destruction highlights the energy inefficiencies within a system and provides useful information to the managers and decision makers for prioritizing the improvement potentials. Exergy analysis is generally an applicable method for the comparison of the alternative processes for a given purpose.

In this study, thermal spray process techniques (APS, SPS, HVOF, HVSFS) as energy intensive manufacturing processes are analyzed and compared on the basis of exergy and energy analysis methods. For a comprehensive evaluation, energy efficiency as well as exergy efficiency and exergy destruction are proposed as the indicators.

This work concludes with a discussion of the advantages of the exergy analysis method in comparison with a conventional energy efficiency evaluation by validation of the results for the case of thermal spray processes.

Selection and peer-review under responsibility of the International Scientific Committee of "The 47th CIRP Conference on Manufacturing Systems" in the person of the Conference Chair Professor Hoda ElMaraghy"

Keywords: Energy and exergy efficiency; Exergy destruction; Thermal spray process

1. Introduction

Nowadays manufacturing companies are facing diverse economic and environmental challenges. Especially the attention to global warming, resource depletion and increasing energy and raw material prices are exerting pressure on companies to implement strategies for sustainability. Energy efficiency is considered as a necessary paradigm toward sustainable manufacturing and company's management issues [1]. Recent studies driven from researches as well as industrial practices also underline the importance of energy efficiency and reduction of energy consumption in manufacturing processes. The main motivation is clearly to decrease energy costs while the contribution towards environmental protection [2]. In manufacturing processes, part of the process energy demand is lost as heat and emissions to the environment as well as through the irreversibilities within the process [1]. The aforementioned energy inefficiencies result in significant losses from the already limited available energy sources and therefore constit-

Selection and peer-review under responsibility of the International Scientific Committee of "The 47th CIRP Conference on Manufacturing Systems" in the person of the Conference Chair Professor Hoda ElMaraghy"
doi:10.1016/j.procir.2014.01.060

Nomenclature

C_p	heat capacity (KJ/kg.k)
E	energy (MJ)
Ex	exergy (MJ)
$\dot{m}$	mass flow rate (kg/s)
$\dot{Q}$	heat rate (KJ/h)
r	specific gas constant
p	pressure
T	temperature (°C or k)
ΔT	temperature difference

Subscripts

0	dead state (environment) condition
De	destructions
in	input
loss	losses
(M)	mechanical
out	output
P	productive
S	system
(T)	thermal

Greek letters

ψ	exergy efficiency (%)
η	energy efficiency (%)

Abbreviations

APS	Air Plasma Spray
FLT	First Law of Thermodynamics
HVOF	High Velocity Oxy-fuel Flame spray
HVSFS	High Velocity Suspension Flame Spray
SLT	Second Law of Thermodynamics
SPS	Suspension Plasma Spray

-ute extra undesirable energy costs and environmental penalties for the companies [2]. With the increase need to reduce the impacts of waste energy on the environment and the need to reduce energy demand, it is becoming extremely important to develop even more accurate and systematic energy efficiency approaches for evaluation of energy optimization potentials and prevention of wrong improvement decisions [4].

Altogether, along with management approaches, thermodynamics methodologies strongly contribute toward the improvement of energy efficiency in manufacturing processes. In contrast to conventional energy balance of the first law of thermodynamics (FLT), process analysis based on second law of thermodynamics (SLT) and exergy definition can realistically determine the location and magnitude of energy losses as well as useful amount of energy recovery potentials from the waste heat [3]. The application of exergy analysis has recently received increasing recognition by many researchers in industry as a powerful tool for assessing and improving energy efficiency [5–6] and as an applicable method for comparing different processes techniques for a given purpose [7]. In the current literature the benefits of exergy analysis in comparison with energy analysis is validated for thermal spray process as an energy intensive manufacturing process. To the best of the author's knowledge, no studies appear in literature to make an effort to exergy and energy based analysis of thermal spray process techniques.

Structure

This study encompasses the following main contents:

- propose exergy analysis as a novel energy optimization approach for manufacturing and industrial processes
- Represent the benefits of exergy analysis compare to conventional energy efficiency analysis method with a case study. Besides energy balance, exergy balance was conducted for evaluation and comparison of thermal spray process techniques - high velocity oxy-fuel flame spray (HVOF), high velocity suspension flame spray (HVSFS), air plasma spray (APS), suspension plasma spray (SPS). Spraying torch and cooling water route were considered as the analyzed boundary.

1.1. Energy and Exergy analysis

True evaluation of energy inefficiencies of processes should now be an important factor in the design and optimization of manufacturing and industrial systems. The exergy method is directed to providing detailed information about the energy losses by a systematic approach that can be easily added to conventional design and performance calculation procedure [3]. Technically, exergy is defined using thermodynamics principles as the maximum amount of work which can be produced by a system or a flow of matter till the system or the flow comes to equilibrium with a reference environment [8-9]. According to the SLT, part of the energy consumption by a manufacturing process is lost due to the irreversibilities and increases entropy within the system. Exergy analysis is relevant for identifying and quantifying both of exergy destruction within a process due to irreversibility (cannot be used to to work and should be possibly eliminated) and the exergy losses e.g. the transportation of exergy to the environment. Exergy destruction is neglected in the evaluation of a system according to energy balance of first of thermodynamics. These energy inefficiencies help to highlight the areas of energy improvement potentials within a system and also from the impact on the environment [4]. The overall energy and exergy balance for a system is illustrated in Fig.1. For the energy analysis we have:

$$E_{in} = E_{out} + E_{loss} \tag{1}$$

$$\eta = \frac{E_{out}}{E_{in}} = \frac{E_{in} - E_{loss}}{E_{in}} \tag{2}$$

Where energy efficiency (η) is defined as the ration of output energy (E_{out}) to the input energy (E_{in}) and the enegy loss is represented by E_{loss}. In contrast to energy balance, exergy balance comprises exergy destruction as an additional indicator of exergy loss. The exergy desctruction is discriminated from the exergy loss since it shows the amount

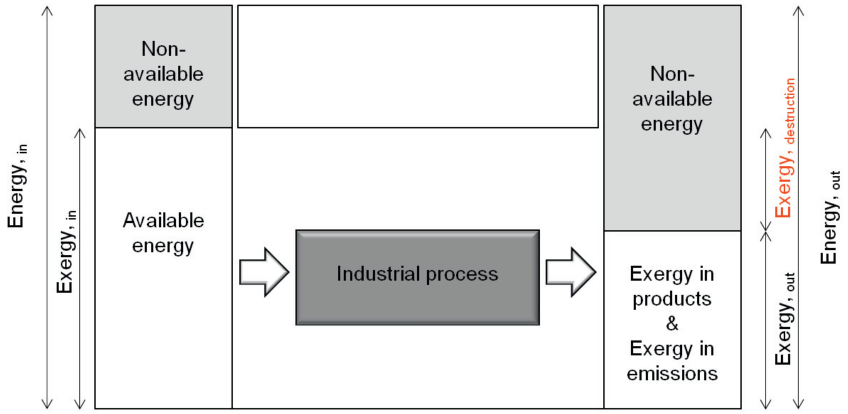

Fig.1. System energy and exergy balance

of useful energy which is dissipated within a process due to irriversibilities such as friction, expansion, hydraulics and etc.

$$Ex_{in} = Ex_{out,p} + Ex_{out,loss} + Ex_{De} \tag{3}$$

$$\psi = \frac{Ex_{out,p}}{Ex_{in}} = 1 - \frac{Ex_{loss} + Ex_{De}}{Ex_{in}} \tag{4}$$

In the exergy efficiency definition (ψ), $Ex_{,in}$ is input exergy and $Ex_{,out,p}$ is productive exergy output. $Ex,_{out,loss}$ and $Ex,_{De}$ represent exergy loss and exergy destruction respectively.

Here, the exergy efficiency (ψ) frequently gives a finer understanding of performance than energy efficiency (η). Exergy efficiency is usually defined, as utilized exergy divided by used exergy. This should be in an interval between 0 and 1, since all real processes involves exergy destruction. This is in distinction to energy efficiency which may well exceed 1 [10].

The FLT defines internal energy as a state function provides a formal statement of the conservation of energy. However, it provides no information about the inability of any thermodynamics processes to convert heat into mechanical work with full efficiency [11]. To analyze a system, all in-flow and out-flow energies need to be considered. In energy analysis, amount of heat transfers through the system's boundary is calculated by Eq.5.

$$Q = \dot{m}c_p \Delta T \tag{5}$$

However, in exergy analysis, the characteristics of the reference environment must be specified in the calculation. Understanding of SLT and Carnot's efficiency, describes that not all the thermal energy can be transformed into work. The exergy of a heat stream depends on the temperature of the reference environment and therefore is expressed as a factor of Carnot's efficiency refers to Eq.6.

$$Ex = (1 - \frac{Tc}{T_H})\dot{Q} \tag{6}$$

where T_c is the temperature of a cold system and T_H is the temperature of a hot system [12]. Considering one of the systems as the reference environment, exergy is zero when system is in equilibrium with the reference environment [13]. For an open system with mass and energy flow assuming that potential and kinematic energy are negligible and no chemical reaction occurs, the exergy of each stream can be expressed as the summation of mechanical $Ex_{(M)}$ and thermal $Ex_{(T)}$ exergy.

$$Ex = Ex_{(M)} + Ex_{(T)} \tag{7}$$

$$Ex_{(M)} = \dot{m}rT_0 \ln \frac{p}{p_0} \tag{8}$$

$$Ex_{(T)} = \dot{m}c_p[(T_s - T_0) - T_0(\ln \frac{T_s}{T_0})] \tag{9}$$

For all in-flow and out-flow, T_s indicates respective flow temperature and T_0 is the temperature of the reference environment [*6*].

2.2 Analyzed boundary for thermal spray process

For developing future financial strategies, high energy intensive manufacturing processes need to be optimized for energy saving potentials. To get into the topic, in this study four thermal spray process techniques for manufacturing of Al_2O_3 coating were compared. The analyzed boundary as it is shown in Fig.2 includes the spray torch and cooling water route. The required thermal energy demand is supplied by: electrical power for APS and SPS processes and thermal energy from ethane combustion for HVOF and HVSFS processes. A conventional plasma torch for the plasma spraying and Top-Gun torch for flame spraying were applied. The basis for the comparison (functional unit) was a manufacturing coating of microstructure-100 µm of Al_2O_3 on 1-dm^2 substrate. According to given parameters in table.1, powder of Al_2O_3 was applied as feedstock material in APS and HVOF, whereas a solution of Al_2O_3 was used in SPS and HVSHS processes for manufacturing of Al_2O_3 coating on the substrate. The Al_2O_3 content of the solution is 20%. Thus to produce the same amount of coating, longer spraying time is

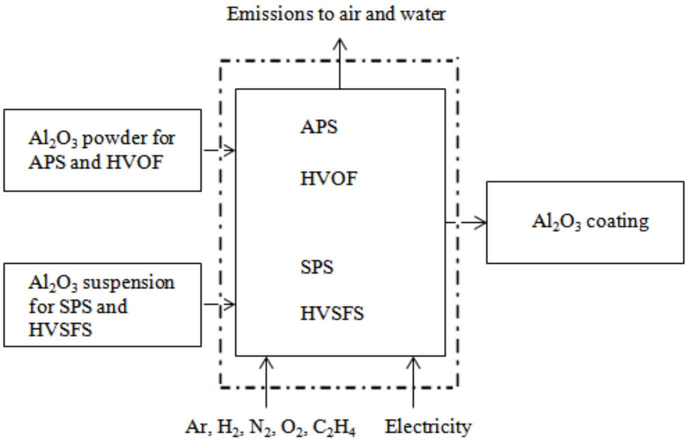

Fig.2. Thermal spray process boundary for manufacturing of Al_2O_3 coating

needed for the processes with solution feedstock.

Table.1. Parameters for Al_2O_3 plasma and flame spraying

Spray process	APS	SPS	HVOF	HVSFS	Unit
Coating porosity	10-20	10-30	50		%
Ar	42.5	42.5			l/min
N_2			25	25	l/min
H_2	8	8			l/min
O_2			250	250	l/min
Ethane			95	95	l/min
Current	552	552			A
Power	38	38			kW
Cooling water	14.4	14.4	34.3	34.3	l/min
Al_2O_3	35	7	35	7	g/min
Material	Al_2O_3 Powder	20% Al_2O_3 in water	Al_2O_3 powder	20% Al_2O_3 in water	

Table.2. Cooling water parameters

Cooling water parameters	T_1	T_2	T_0	Unit
APS & SPS	18.6	37.4	25	° C
HVOF & HVSFS	15	22.8	25	°C

3. Results and discussion

Energy efficiency has been conventionally used as an indicator for energy evaluation of the manufacturing and industrial processes. The benefits of exergy efficiency and exergy destruction are analyzed for the case of thermal spray process in this work. Considering the fact that both exergy destruction and exergy efficiency as energy indicators will provide a more comprehensive understanding of the process improvement potentials and a more applicable approach for comparison of alternative processes.

In thermal spray process it was assumed that the total consumed energy was converted into heat in the torch. Part of the heat is used as the thermal energy for melting of material and manufacturing of coating and the rest is wasted as heat loss. According to FLT and energy balance, with the given parameters from Table.1 and Table. 2, energy efficiency was calculated by Eq.1 and Eq.2. For exergy analysis and with the assumption of no exergy destruction for the torch exergy input, exergy efficiency of the torch was evaluated from Eq.3 and Eq.4. Due to high process temperature, the exergy destruction of the torch is very small and therefore there was not a big difference between energy and exergy efficiency results.

From Eq.9 only a small quantity of the waste heat can be absorbed by the cooling system. This can be mainly represented by the low temperature difference of inflow and outflow of cooling water with surrounding environment. Therefore, the system reaches to equilibrium with its environment very early.

3.1 Comparison of energy and exergy efficiency

From the energy and exergy efficiency of thermal spraying torch, HVOF and HVSFS processes show in overall the higher efficiency compare to APS and SPS processes. This can be proved by the higher energy and exergy input.

With the high process and torch temperature, 3300 k for APS and SPS and 2200 k for HVOF and HVSFS, Carnot's efficiency is high and therefore according to Eq.6 exergy values are almost equal to energy values. As a result, the destruction of exergy of the torch is quite small. However, as is seen in Fig.3, even a small amount of exergy destruction resulted in 5-10% difference between energy and exergy efficiencies.

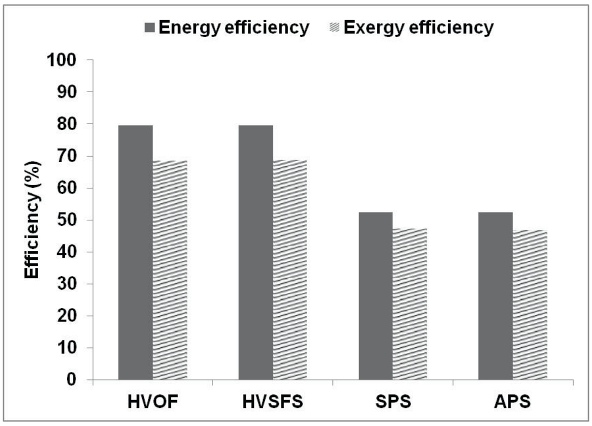

Fig.3. Comparison of energy and exergy efficiency for thermal spraying torch

3.2 *Exergy destruction*

Form the Carnot's efficiency in Eq.6, the higher the temperature leads to the higher exergy and lower exergy destruction. Since thermal spray process is working at very high temperature, the main part of the produced heat is useful and converted to the heat and only a small part of heat is destructed. The results represent that spraying time and torch temperature are the important parameters for analysis of exergy destruction. For detailed analysis as is illustrated in Fig.4, exergy destruction for HVSFS is remarkably high compare to other processes. This can be interpreted in the aspect of longer spraying time compare to APS and HVOF and lower torch temperature in comparison with SPS process.

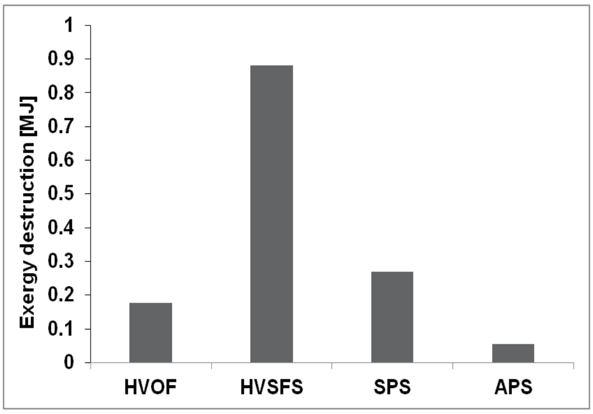

Fig.4. Exergy destruction in torch (100 μm of Al_2O_3 on 1dm^2 surface)

According to Fig.5 the exergy destruction of cooling water route is significantly higher that of the torch. The exergy analysis results represent that only small part of the heat loss from the torch was absorbed by the cooling water and the rest increased the entropy within the system and destructed. Generally, the exergy destruction of the torch and cooling water route for the processes with longer spraying time is higher. Despite exergy efficiency for the processes with the same spraying torch is almost equal, respective exergy destruction is quite different and is a practical indicator for comparison of the processes.

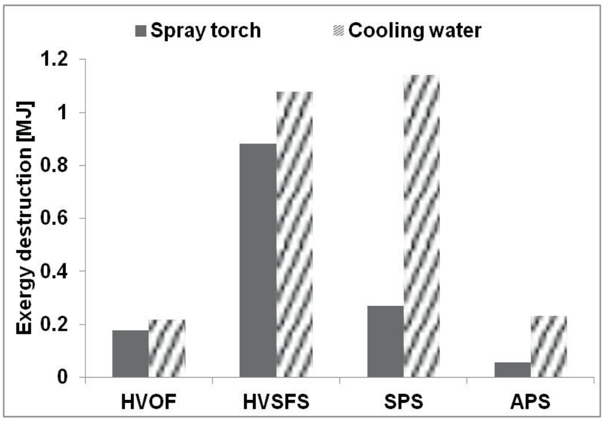

Fig.5. Comparison in torch and cooling water exergy destruction of thermal spraying processes

3.3 *Effect of increase of coating surface on exergy destruction*

Thermal spray process analysis also carried out for coating a substrate with 100 μm of Al_2O_3 on 100 dm^2 surface. By increase of coating surface and respective spray time, exergy destruction was increased within the process. Refers to section 3.2, spraying time highly influences on exergy destruction in thermal spray process.

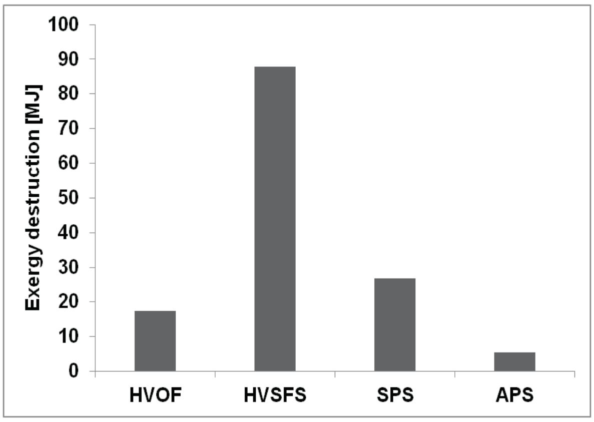

Fig.6. Exergy destruction in torch (100 μm of Al_2O_3 on 100 dm^2 surface)

With an assumption of the same feedstock feeding rate, though the energy and exergy efficiency for all thermal spray process techniques remained unchanged, increase of the spraying time by using either solution feedstock or increasing coating surface, amplified the exergy destruction. The results are shown in Fig.6 and can be compared with the results of Fig.4.

This case study clearly shows the advantages of combining exergy efficiency and exergy destruction for alternative processes comparison and prioritization of the energy improvement potentials for a process. In general from efficiency evaluation, even small exergy destruction in the torch resulted in 5-10% difference of energy and exergy efficiencies. Also contradicts with the conventional energy balance, exergy destruction showed that the exchange of heat loss from torch to the cooling water is small and the main part of the heat loss is destructed in the cooling system. In other words, the cooling system power is quite lower than that was expected from energy analysis. From the environmental point of view, only the exchanged heat into the water can be considered as the potential heat to be recovered or to have environmental impacts. From the perspective of process optimization, exergy destruction in all system components needs to be reduced and possibly eliminated. In this case study, the higher exergy destruction in cooling water route compare to the torch shows its priority for improvement.

4. Conclusions

Along with increase of productivity, reduction of the energy demand and energy cost has become important issue of the manufacturing companies. In the road of sustainable production and from the environmental and economical perspectives, both management approaches and energy efficiency practices with the aim of energy saving are the matters of essence. The benefits of exergy analysis for energy evaluation of a manufacturing process have been verified. Exergy analysis has been introduced as a practical energy analysis method for energy system evaluation. It provides comprehensive information for prioritizing energy optimization by magnifying energy losses and heat recovery potentials in manufacturing units as well as being a powerful tool for comparing the alternative processes for a given purpose. Altogether, provided analysis based on exergy efficiency and exergy destruction is playing a major role for system's energy improvement which these measurements are not provided by the energy analysis method.

References

[1] Thiede S. Energy Efficiency in Manufacturing System. Herrmann C, Kara S., editors. Springer; 2012. p. 1-6.

[2] Thamling N, Seefeldt F, Glöckner U. Rolle und Bedeutung von Energieeffizienz und Energiedienstleistungen in KMU: Prognos AG, Basel; 2010.

[3] Ahern J. The exergy method of energy systems analysis. Wiley Inc.; 1980. p. 1-36

[4] Kelly P. Energy systems improvement based on endogenous and exogenous exergy destruction. Dissertation. Berlin; 2008.

[5] Dincer I, Rosen A. Exergy, Energy, Environment and Sustainable Development. Elsevier: Oxford, UK; 2013.

[6] Moran J, Shapiro .N, Boettner D, Bailey B. Fundamentals of Engineering Thermodynamics. Wiley: New York, USA; 2011.

[7] Kim MY, Lee HJ, Kim JS, Favrat D. Potential and Evolution of Compressed Air Energy Storage: Energy and Exergy Analyses. Entropy; 2012.

[8] Moran J. Availability Analysis: A Guide to Efficient Energy Use, revised ed. ASME, New York; 1989.

[9] Rosena M, Dincera I, Kanoglu M. Role of exergy in increasing efficiency and sustainability and reducing environmental impact. Energy policy; 2007.

[10] Ruixian Cai, et al. Eds. On exergetics, economics and optimization of thechnical processes to meet environmental conditons. International Conference on **T**hermodynamic **A**nalysis and **I**mprovement of **E**nergy **S**ystems. Beijing; 1997. p. 453-460.

[11] Dincer I, Cengel Y. Energy, Entropy and Exergy Concepts and Their Roles in Thermal Engineering. Entropy; 2001.

[12] Jentsch A. A novel exergy-based concept of thermodynamic quality and its application to energy system evaluation and process analysis. Disseration. Berlin; 2010.

[13] Rosena M, Dincera I, Kanoglu M. Role of exergy in increasing efficiency and sustainability and reducing environmental impact. J Energy policy; 2007.