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Life Cycle Assessment (LCA) Study Of High Entropy Alloy Geo-Coat Technologies Deposited Through High-Velocity Oxy-Fuel Thermal Spraying, Laser Cladding And Electro-Spark Deposition Processes

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ABSTRACT

The aggressive nature of the medium to high-temperature geothermal resources makes the geothermal plant components vulnerable to corrosion, erosion and scaling. Hence, keeping the integrity of the various plant components is a big challenge nowadays. To combat the corrosive geothermal environment, the Geo-Coat project proposes the components to be made of carbon steel and coated with cost-effective corrosion-resistant, erosion-resistant and antiscaling materials. Five high entropy alloys (HEAs) coating materials deposited through High-Velocity Oxy-Fuel spray (HVOF), Laser Cladding (LC) and Electro-Spark Deposition (ESD) have been studied. Determining the environmental impacts of these coating materials and their deposition processes is an essential step in designing a green and sustainable technology. Therefore, in this study, the environmental impacts of these HEA coatings have been evaluated by a cradle to gate approach, by using SimaPro 9.0.0.49 LCA tool, and life cycle impact assessment (LCIA) methodology IMPACT 2002+, version 2.14. For life cycle inventory (LCI) data of the study, ecoinvent 3.4 database has been used. The environmental impacts of these material syntheses have been evaluated through quantification of the midpoint impacts and endpoint damage categories. This paper briefly presents the results of the LCIA and suggests the best combination of coating material and its deposition technique, which can be used for identifying and promoting green and sustainable coatings for geothermal plant components.

1. INTRODUCTION

The coatings play a vital role against corrosion, erosion and scaling in extending the lifetime of geothermal components such as pipes and casings, heat exchanger tubes, and others. Geo-Coat is aimed to develop high performance synthesised coatings for geothermal components. The excellence of the Geo-Coat lies in the concept of developing innovative synthesised coatings, also referred to as Geo-Coat technology addressing corrosion, erosion-corrosion and scaling damages due to aggressive environment of medium to high temperature geothermal resources. In this study, we are investigating the environmental impacts caused by different stages of the high entropy alloy coatings developed for geothermal components. A life cycle assessment (LCA) tool, SimaPro 9.0.0.49 [1], has been used to calculate and evaluate the environmental performances of these synthesised coatings deposited onto the substrates through HVOF, LC and ESD processes. The functional unit of this LCA study is 1 µm thick coating over 1 m^2 area of substrate. The LCA methodology applied in this study follows the methodology defined by the ISO14040 and ISO14044 standards [2]. LCA is a structured, internationally standardised method for quantifying the emissions, resources consumed and environmental and health impacts that are associated with products or processes. LCA is carried out in four basic, interdependent stages: goal and scope definition, inventory analysis, impact assessment, and interpretation. Environmental performances of the synthesised coatings have been studied using the cradle-to-gate life cycle approach. The main goal of the LCA studies of the synthesised coatings is to assess the environmental impacts; the following goals should be achieved:

- Quantify and evaluate the environmental performances of the synthesised coatings deposited through HVOF, LC and ESD processes.
- Identify the green and sustainable synthesised coatings.

The scope of the study is to establish the baseline information to produce coatings and then comparing the environmental impacts. The scope of the comparison includes:

- Coating elements and processes used to manufacture five HEA coating materials (HEA1-HEA5). Manufacturing of infrastructure equipment, e.g., equipment used for mechanical alloying, gas atomisation etc, is excluded from the LCA.
- Coating deposition processes used for deposition of coating materials: HVOF thermal spraying, LC and ESD. We exclude the manufacture of the infrastructure equipment (e.g., spray gun, powder feeder, robotics, electroplating tanks, etc) and
- Substrate surface preparation processes: grit blasting and grinding linisher methods (excluding the manufacturing of the infrastructure materials of grit blasting and grinding machines);

Specifically, the scope of the study of synthesised coatings will be focused on:

- Cradle to gate analysis which will quantify the environmental impacts of the required materials and energy needed to produce the HEA coating materials.

- Gate to gate analysis which will cover the environmental impacts of different processes involved in substrate preparation and coating material production and deposition.

The system boundary for LCA studies of the synthesised coatings is presented in Figure 1.

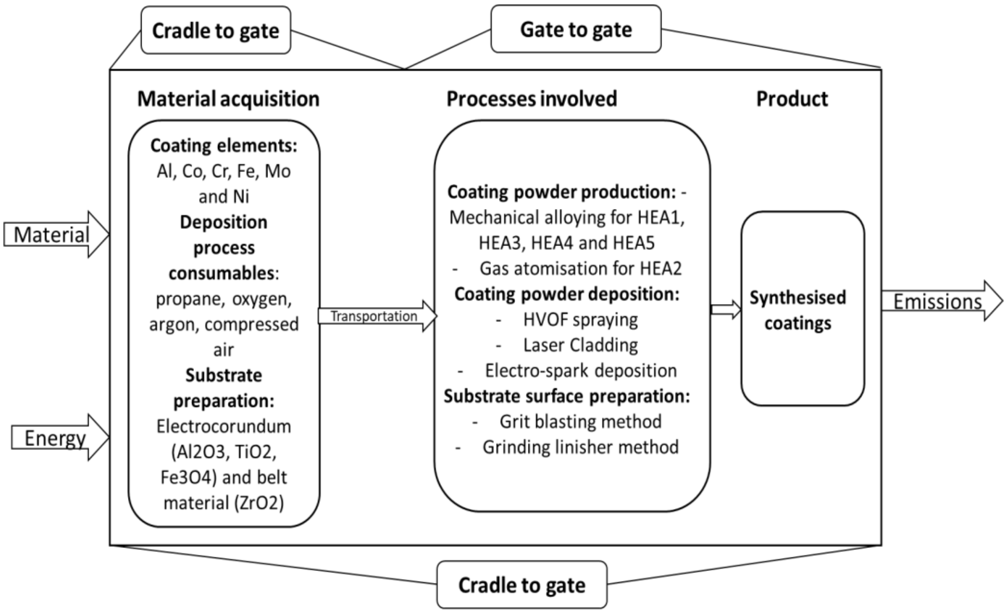

Figure 1 - A system boundary for LCA studies of synthesised coatings.

The system boundary of LCA analysis also includes transportation of coating materials and other consumables. Due to the unavailability of some primary processing data, we have calculated and estimated the data based on assumptions and secondary sources.

The Life Cycle Inventory (LCI) building is a fundamental basis necessary to carry out environmentally based assessment LCA. LCI data of synthesised coatings were mainly collected from primary sources. Some data are estimated and calculated from secondary sources [3]. All the data were normalised to the study functional unit of 1 μm thick coating over 1 m^2 substrate area and then imported into SimaPro9.0.0.49, a commercially available LCA tool. It is designed to allow flexibility in conducting life-cycle design and cradle to gate LCA functions and to provide the means to organise inventory data, investigate alternative scenarios, evaluate impacts, and assess data quality. We have also explored inventory data from ecoinvent version 3.4 database for various elements and consumables. All these data inventories are described and listed in section 2. The Life Cycle Impact Assessment (LCIA) methodology used in this LCA study is the IMPACT2002+ V2.14 / IMPACT 2002+ which is compliant with the ISO 14040 series. The IMPACT 2002+ LCIA methodology proposes a feasible implementation of combined midpoint impacts and endpoint damage approaches, linking all types of LCI results (elementary flows and other interventions) via 15 midpoint impact categories to 4 endpoint damage categories [4]. The purpose of life cycle impact assessment (LCIA) is to interpret the life cycle emissions and resource consumption inventory in terms of indicators for the Areas of Protection (endpoint damage categories), i.e., to evaluate the impact on the entities that we want to protect. The four endpoint damage categories considered in the IMPACT 2002+ methodology are human health, climate change, ecosystem quality and resources. The LCIA results of all synthesised coatings i.e., Geo-Coat technologies under study have been evaluated and given in section 3. Finally, we have concluded the green and sustainable Geo-Coat technology based on the environmental impact results.

2. DATA INVENTORIES

In order to produce equimolar or nearly equimolar high entropy alloys (HEAs) by mechanical alloying and gas atomising methods, high purity metallic powders of Al, Co, Cr, Fe, Ni and Mo were used. All metallic powders have been mechanically alloyed under argon atmosphere in a high-speed planetary ball mill (Pulverisette 6, Frich®) for HEA1, HEA3-5 coating powders. Milling time has been varied in order to choose the best ratio between time and alloying degree. The alloying of metallic powders for HEA2 coating powder has been performed using the gas atomiser (Hermiga 100/10 VI Atomiser, PSI). The elemental composition of 5 different HEAs (HEA1-HEA5) coating powders and the production methods are given in Table 1.

Table 1 - Elemental compositions of the coating materials HEA1-HEA5 and their production methods

Coating ID	Coating compositions	Production process	Elemental composition (wt%)					
			Al	Co	Cr	Fe	Ni	Mo
HEA1	CoCrFeNiMo0.85	Mechanical alloying	-	19.19	19.19	19.19	19.19	23.24
HEA2	CoCrFeNiMo0.85	Gas atomising	-	19.19	19.19	19.19	19.19	23.24
HEA3	CoCrFeNiMo	Mechanical alloying	-	18.34	16.18	17.38	18.26	29.84
HEA4	Co0.5CrFeNiMo	Mechanical alloying	-	10.09	17.81	19.13	20.11	32.86
HEA5	Al0.5CoCrFeNiMo	Mechanical alloying	8.55	18.34	16.18	17.38	18.26	21.29

To produce 1 kg HEA coating powders, the energy consumption was calculated using the processing time and the power of the machines involved. Table 2 lists the energy consumptions for HEA1-HEA5 coating powders, along with argon consumption.

Table 2 - Electrical energy and argon consumption for HEA1-HEA5 coating powders.

Coating ID	Mass of coating material	Processing time	Power of machines	Mass of Argon consumables	Electrical energy
	(kg)	(min)	(kW)	(kg)	(kWh)
HEA1	1	90	1.1	0.24	1.65
HEA2	1	4	10	0.24	0.67
HEA3	1	90	1.1	0.24	1.65
HEA4	1	90	1.1	0.24	1.65
HEA5	1	90	1.1	0.24	1.65

The HEA1-HEA5 coating powders have been deposited onto the substrate through the HVOF thermal spraying method. The power levels for HVOF gun working with gases was 100 kW (OERLIKON Metco DJ9W) and other accessories (powder feeder, robotics, diamond jet and others) was 7.5 kW. In the HVOF process with HEA powders deposition, the main parameters are flow rates of oxygen, propane, air and powder feed rate. The total thickness of the coating deposited over 1 m^2 area was 145 µm thick for all HEA1-HEA5. The data inventory for HVOF deposition method is given in Table 3.

Table 3 - HVOF deposition process data for all HEA1-HEA5 coating materials

Process parameters and others	Unit	Amount
Time of deposition	min	100
coating powder flow rate	g min^{-1}	35
Total mass of the coating material deposited (calculated)	g	3500
Oxygen flow rate	slpm	295
Propane flow rate	slpm	68
Air flow rate	slpm	357
Total electrical energy consumed (calculated)	kWh	179.2
Total oxygen consumed (calculated)	kg	42.2
Total propane consumed (calculated)	kg	13.7
Total air consumed (calculated)	m^3	35.7
Total heat energy consumed due to propane burned (calculated)	MJ	638.9

The HEA1-HEA5 coating powders have also been deposited onto the substrate through the Laser Cladding (LC) process. The main parameters for the LC process are laser power, argon flow rate, and powder feeding rate. The total deposition time for all respective passes for 1 m^2 coating area has been calculated using laser head speed (10 mm s^{-1}) and the distance between tracks of 0.71 mm. The coating powder flow rate was 2 g min^{-1}. The data inventory of LC deposition process for HEA1-HEA5 coating materials over 1 m^2 area is given in Table 4.

Table 4 - LC deposition process data for HEA1-HEA5 coating materials deposited over 1 m^2 area

Process parameters and others	HEA1	HEA2	HEA3	HEA4	HEA5
Power of LC machine (kW)	0.55	0.55	0.40	0.45	0.55
Number of passes	2	1	3	2	3
Deposition time (min)	4695	2347	7042	4335	7042
Total thicknesses of the coating (µm)	1053	673	396	537	1690
Mass of coating material deposited (g)	9390	4694	14084	8670	14084
Argon flow rate (slpm)	10	9.5	10	10	10
Mass of argon consumed (kg)	70.43	33.45	105.63	65.03	105.63
Total electrical energy consumed (calculated) (kWh)	43.04	21.51	46.95	32.51	64.55

The HEA1-HEA5 coating powders have been pressed and sintered in order to obtain a final bulk material that can be further processed. The bulk material needs to hold its shape and have a good mechanical resistance so that electrode rods can be machined and used for ESD coating deposition process. The HEA1-HEA5 coating rods have also been deposited onto the substrate through Electro-spark deposition (ESD) process. The total thickness of the coating deposited over 1 m^2 area was 400 µm thick for all HEA1-HEA5. The data inventory for ESD deposition method is given in Table 5.

Table 5 - ESD deposition process data for all HEA1-HEA5 coating materials

Method	Unit	Values
Power of ESD machine	kW	2
Time of deposition	min	42
Voltage	V	100
Capacitance	µF	40
Pulse rate	Hz	500
Argon flow rate	slpm	3
Power of the pressing rod machine	kW	1

For an LCA study, the functional values of masses of coating materials and consumables, energies and transportation flows for 1 µm thick HEAs coatings deposited over 1 m^2 area through HVOF, LC and ESD processes have been evaluated using the data given in Tables 3, 4 and 5 and listed in Table 6, 7 and 8, respectively.

Table 6 - Functional values of mass, energy and transportation flows for 1 µm thick HEA coating deposited over 1 m^2 area using HVOF process

Coating ID	Coating Material	Oxygen	Electrical energy	Transportation	Heat energy due to propane burned	Compressed air
	(kg)	(kg)	(kWh)	(tkm)	(MJ)	(m^3)
HVOF_HEA1-HEA5	0.024138	0.291034	1.235862	0.058207	4.406207	0.246207

Table 7 - Functional values of mass, energy and transportation flows for 1 µm thick coatings (HEA1-HEA5) over 1 m^2 area using LC deposition process

Coating ID	Coating Mass	Argon mass (kg)	Electrical energy	Transportation
	(kg)	(kg)	(kWh)	(tkm)
LC_HEA1	0.008917	0.066885	0.040873	0.013377
LC_HEA2	0.006976	0.049703	0.031961	0.009941
LC_HEA3	0.035566	0.266742	0.118561	0.053348
LC_HEA4	0.016145	0.121099	0.060540	0.024220
LC_HEA5	0.008334	0.062503	0.038195	0.012501

Table 8 - Functional values of mass, energy and transportation flows for 1 μm thick coatings (HEA1-HEA5) over 1 m^2 area using ESD deposition process

Coating ID	Coating Mass	Argon mass	Electrical energy	Transportation
	(kg)	(kg)	(kWh)	(tkm)
ESD_HEA1	0.008682	1.6668	0.0912	0.3335
ESD_HEA2	0.008682	1.6830	0.0838	0.3367
ESD_HEA3	0.008839	1.6668	0.0913	0.3335
ESD_HEA4	0.008833	1.6668	0.0913	0.3335
ESD_HEA5	0.008196	1.6668	0.0907	0.3335

Substrate surface preparation is the essential treatment of a substrate before the application of any coating material deposition through various deposition processes. The performance of a deposited coating material is significantly influenced by its ability to adhere properly to the substrate material. Before applying coating material over the substrate surface through HVOF and ESD deposition processes, we prepared the surface using grit blasting method. The grit material used in this study is electrocorundum composed of 94%, 3.5% and 2.5% of Al2O3, TiO2 and Fe3O4, respectively and the power of grit blasting machine is 1.5 kW. For preparing 1 m^2 surface area of the substrate, the amount of grit materials has been calculated based on primary data provided by the consortium members [5] such as the grit feed rate (2200 g min^{-1}) and the reuse factor (20) of grit materials. We also estimated the manufacturing energy of that amount grit material based on the assumptions and estimation from secondary data source [3] such as the rate of production of grit material (4 kg per hour) and the power of the grit manufacturing machine (1 kW). Based on these primary and secondary data, we evaluated the LCA data of substrate surface preparation for 1 m^2 area before applying coating materials through HVOF and ESD processes. Before the deposition of coating material using the LC process, we apply grinding method to prepare the substrate surface. Likewise, we considered the grinding time, grit feed rate, reuse factor, power of grinding machine and grinding linisher belt production rate, belt production machine power, reuse factor for evaluating the LCA data of substrate preparation for 1 m^2 area before applying the coating materials through LC process. The power of the grinding linisher machine is 3 kW. The dimension of the belt is 914x100x1 mm^3. The density of the belt material is 5680 kg m^{-3}. The belt material is made of zirconium oxide. The average transportation distance for all the materials used in this study is assumed to be 200 km. The calculated inventory data of functional mass of the materials, transportation and energy flows of these substrate preparations are presented in Table 9.

Table - 9 Functional mass of the materials, transportation and energy flows for 1 m^2 surface area preparation using grit blasting and grinding method

Items	Unit	Quantities consumed	
		Grit blasting	Grinding
Aluminium oxide	kg	0.51700	0.51700
Titanium dioxide	kg	0.01925	0.01925
Ferrite	kg	0.01375	0.01375
Zirconium oxide	kg	-	0.25958
Transportation	tkm	0.11000	0.16192
Total electrical energy	kWh	0.26250	0.38750

We have explored inventory data from ecoinvent version 3 database for various elements, consumables and processes used for cradle to gate LCA studies of synthesised coatings. The dataset names for those elements, consumables and processes are listed in Table 10.

Table 10 - Ecoinvent dataset names for the elements, consumables and processes

Elements/consumables/processes	Dataset names
Co	Cobalt {GLO}| production | APOS, U
Mn	Manganese {RER}| production | APOS, U
Cr	Chromium {RER}| production | APOS, U
Ni	Nickel, 99.5% {GLO}| smelting and refining of nickel ore | APOS, U
Fe	Ferrite {GLO}| production | APOS, U
Al	Aluminium, primary {EU27 & EFTA}| production | APOS, U
Ar	Argon, liquid {RER}| production | APOS, U
Transportation	Transport, freight, lorry 16-32 metric ton, EURO6 {GLO}| market for | APOS, U
Electricity	Electricity, medium voltage {GB}| market for | APOS, U
ZrO_2	Zirconium oxide {GLO}| market for | APOS, U
TiO_2	Titanium dioxide {RER}| market for | APOS, U

3. RESULTS AND DISCUSSIONS

We have modelled substrate surface preparation and coating deposition processes to analyse the HVOF_HEA1-HEA5, LC_HEA1-HEA5 and ESD_HEA1-HEA5 synthesised coatings (each of 1 µm thick) deposited over 1 m^2 area of the substrate. The cradle-to-gate LCA analyses of these synthesised coatings have been performed using SimaPro 9.0.0.49, considering the impact assessment method IMPACT 2002+ version 2.14. A snapshot of the SimaPro platform for LC_HEA1 synthesised coating of 1 µm thick over 1 m^2 area is shown in Figure 2.

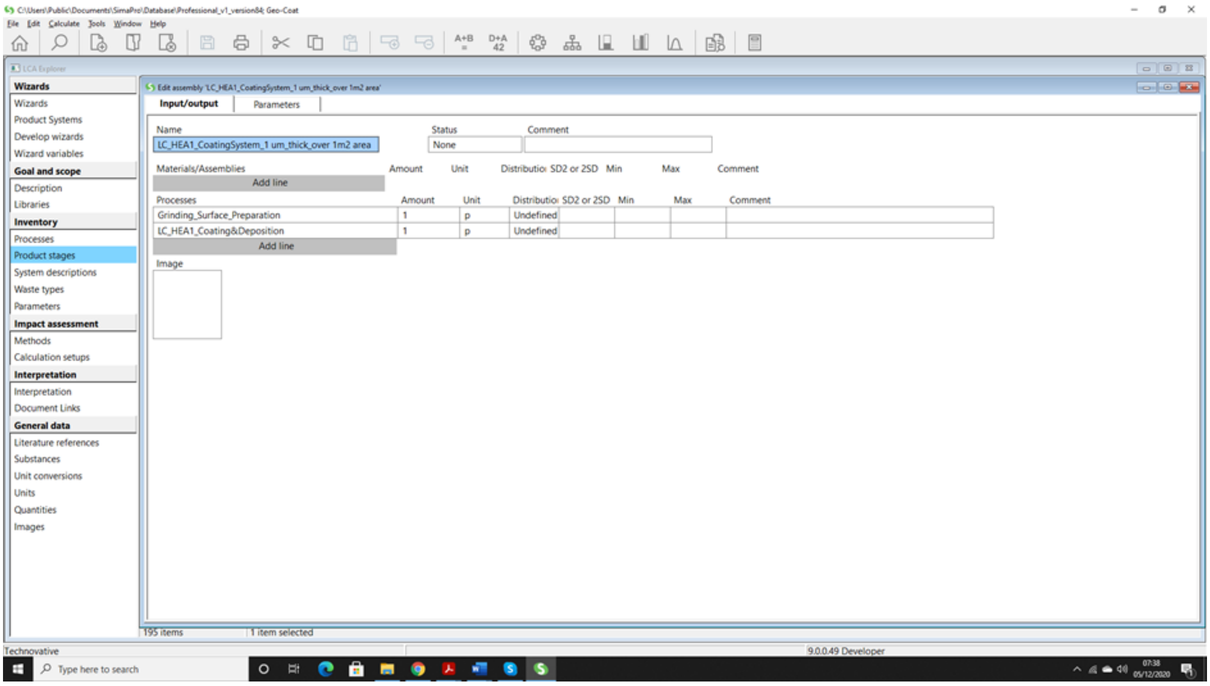

Figure 2 - A snapshot from the SimaPro dashboard of data inventory for 1 µm thick LC_HEA1 synthesised coating over 1 m^2 area.

Using the inventory data of coating materials, coating deposition and surface preparation presented in Tables 6-10, LCA analyses of these synthesised coatings (HVOF_HEA1-HEA5, LC_HEA1-HEA5 and ESD_HEA1-HEA5) each of 1µm thick over 1 m^2 area have been performed. Figure 3 shows a part of the climate change network model for LC_HEA1 synthesised coating of 1 µm thick deposited over 1 m^2 area.

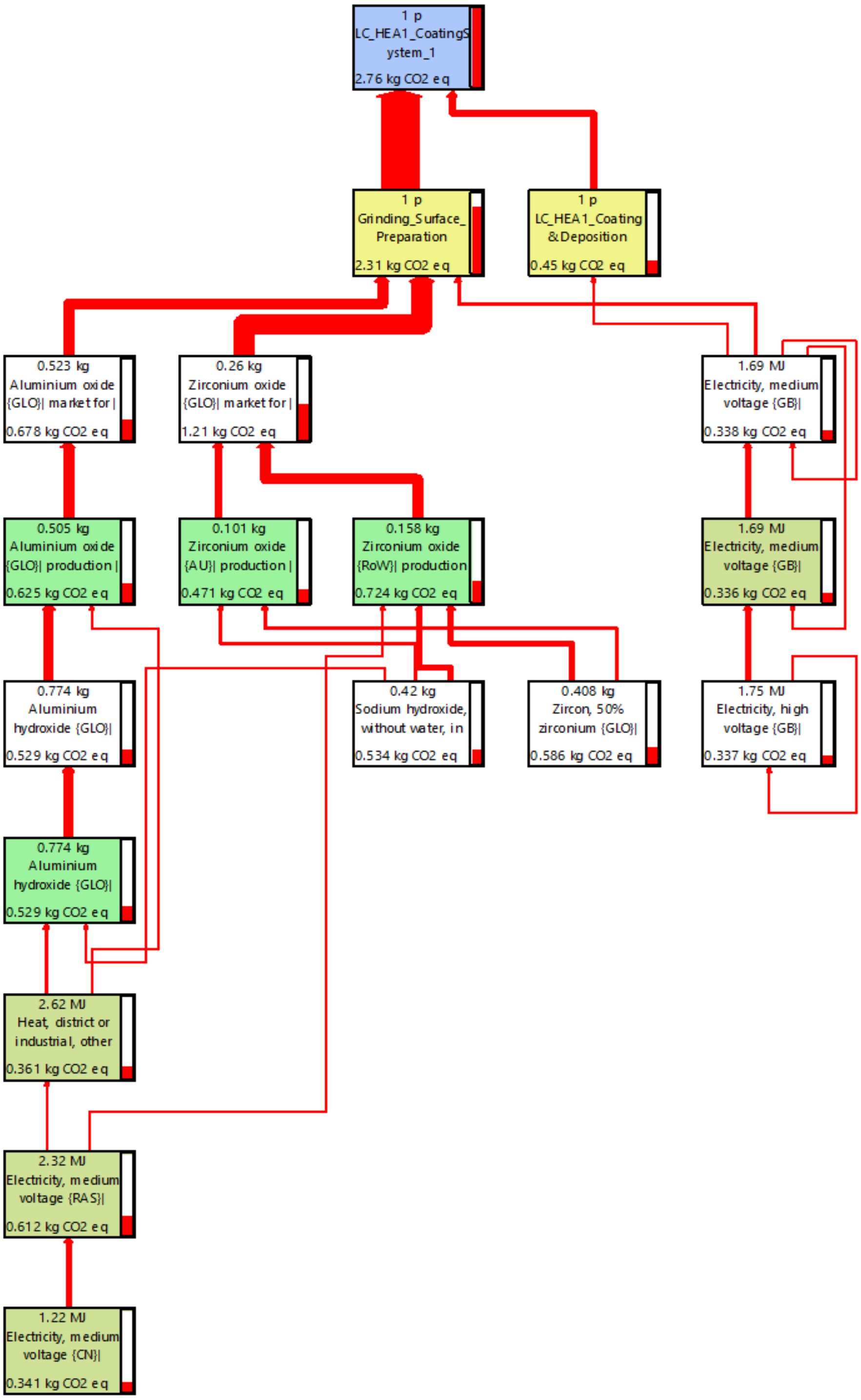

Figure 3 - A network model of climate change damage category for LC_HEA1 (12% cut-off showing 18 nodes out of 11611 nodes) synthesised coating of 1 µm thick over 1 m^2 area.

The cut-off criteria for Figure 3 are 12% which means that the process which contributes less than 12% will not be displayed in the figure. For 12% and above, only 18 nodes are visible out of 11611 nodes. The small thermometers (as shown in Figure 3) attached to the processes give the contribution to the total environmental load. The line thickness also indicates the total environmental load flowing between processes. While a red colour means an environmental load, green means a negative environmental load, or an environmental benefit. Climate change network model is, in general, developed to assess the future impact on climate resulting from the emission of greenhouse gases (and by other activities influencing their atmospheric concentration). Greenhouse gases are substances with the ability to absorb infrared radiation from the earth (radiative forcing). It is seen from the network model of Figure 3 that 1 µm thick LC_HEA1 coating over 1 m^2 area contributing 2.31 and 0.45 kg CO_2 eq. due to grinding surface preparation for the substrate and coating deposition processes, respectively.

The LCIA results of grinding and grit blasting surface preparation of 1 m^2 substrate area have been analysed and given in Table 11.

Table 11 - LCIA results of grinding and grit blasting surface preparation for four endpoint damage categories

Endpoint Damage categories	Unit	Grinding Preparation	Grit Blasting Preparation
Human health	DALY	2.80×10^{-6}	1.32×10^{-6}
Ecosystem quality	PDF*m2*yr	0.53	0.25
Climate change	kg CO2 eq	2.31	1.01
Resources	MJ primary	32.31	14.37

It is seen from Table 11 that the environmental impacts of grit blasting the substrate for surface preparation are about two times lower than those of grinding of substrate for surface preparation, for four endpoint damage categories. The reason for this variation is mainly due to higher resource and energy requirement for grinding process compared to that of grit blasting process.
Figure 4 represents the environmental impacts of 4 endpoint damage categories (human health, ecosystem quality, climate change and resources) for five LC_HEA1-HEA5 synthesised coatings each of 1 μm thick over 1 m^2 area .

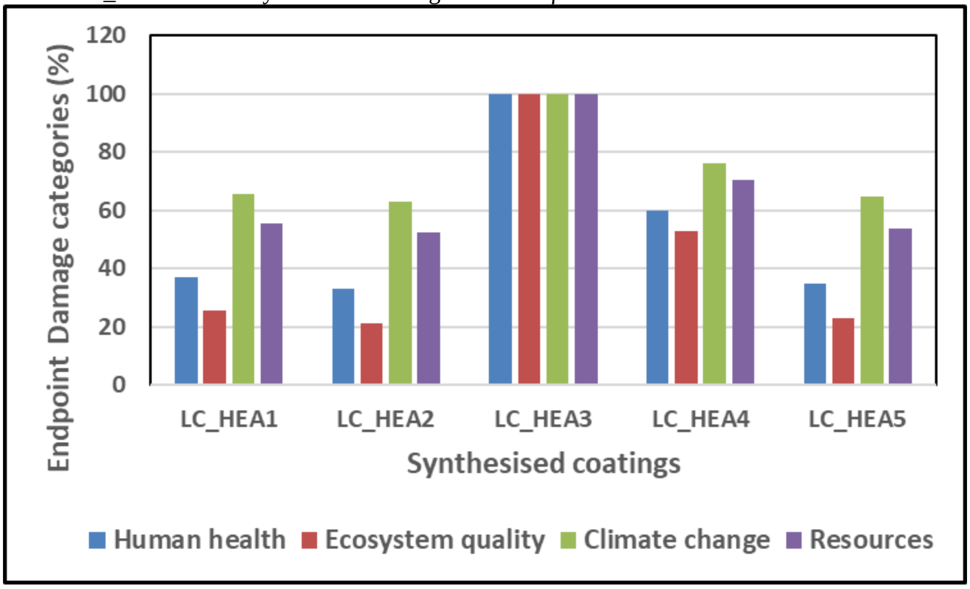

Figure 4 – Environmental impacts of LC_HEA1-HEA5 synthesised coatings for 4 endpoint damage categories.

The quantification of environmental impacts of LC_HEA1-HEA5 synthesised coatings over 4 endpoint damage categories is listed in Table 12.

Table 12 – Quantification of environmental impacts of LC_HEA1-HEA5 synthesised coatings for endpoint damage categories

Endpoint damage categories	Unit	LC_HEA1	LC_HEA2	LC_HEA3	LC_HEA4	LC_HEA5
Human health	DALY	5.06×10^{-6}	4.55×10^{-6}	1.37×10^{-5}	8.19×10^{-6}	4.76×10^{-6}
Ecosystem quality	PDF*m2*yr	1.95	1.64	7.70	4.06	1.75
Climate change	kg CO2 eq	2.76	2.65	4.20	3.21	2.72
Resources	MJ primary	42.00	39.70	76.10	53.50	40.90

The quantified value of four endpoint damage categories has been converted to single score values in terms of point (Pt) and listed in Table 13 including the total score values for five LC_HEA1-HEA5 synthesised coatings.

Table 13 - Single score values of five LC_HEA1-HEA5 synthesised coatings for four endpoint damage categories.

Endpoint damage categories	Unit	LC_HEA1	LC_HEA2	LC_HEA3	LC_HEA4	LC_HEA5
Total	mPt	1.41	1.29	3.42	2.13	1.34
Human health	mPt	0.71	0.64	1.94	1.16	0.67
Ecosystem quality	mPt	0.14	0.12	0.56	0.30	0.13
Climate change	mPt	0.28	0.27	0.42	0.32	0.27
Resources	mPt	0.28	0.26	0.50	0.35	0.27

A graphical presentation of the overall environmental impacts (in terms of single score) of five HEAs deposited through LC process for 4 endpoint impact categories is shown in Figure 5.

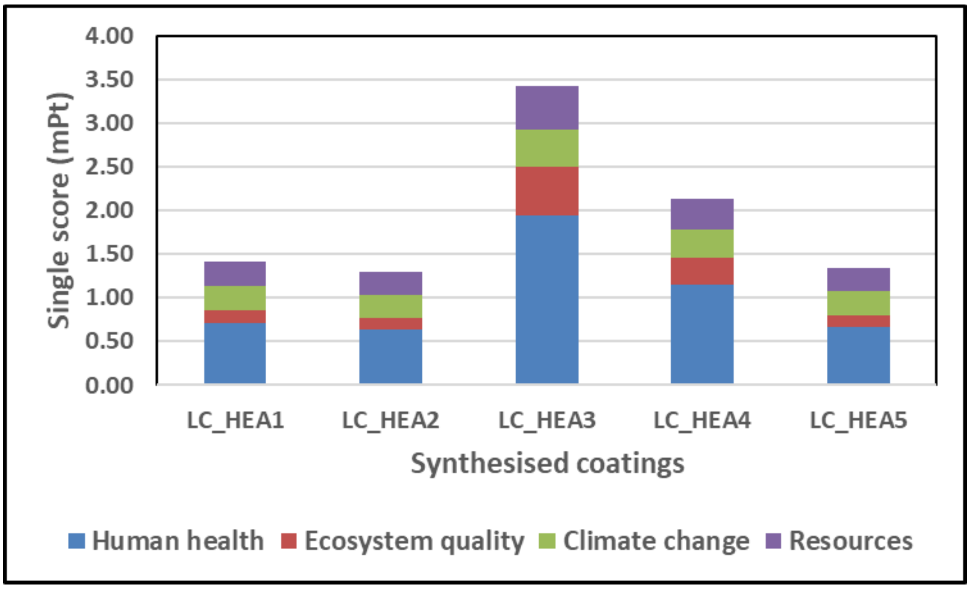

Figure 5 – Single score presentation of the environmental impacts of five LC_HEA1-HEA5 synthesised coatings each of 1μm thick over 1 m^2 area for four endpoint damage categories.

It is evident from the LCIA results (shown in Tables 12 and 13 and Figures 4 and 5) that the synthesised coating LC_HEA2 showed the least environmental impacts as compared with other synthesised coatings mainly due to manufacturing process of HEA2 coating powder.

Five HEA coating powders have been deposited through LC, HVOF and ESD processes. To obtain the environmental impacts of these deposition processes, the LCIA results of the synthesised coatings LC_HEA2, HVOF_HEA2 and ESD_HEA2 each of 1 μm thick over 1 m^2 area have been analysed. Figure 6 shows the environmental impacts of these three synthesised coatings for 4 endpoint damage categories and Figure 7 shows the overall environmental impacts of these three synthesised coatings in terms of single score.

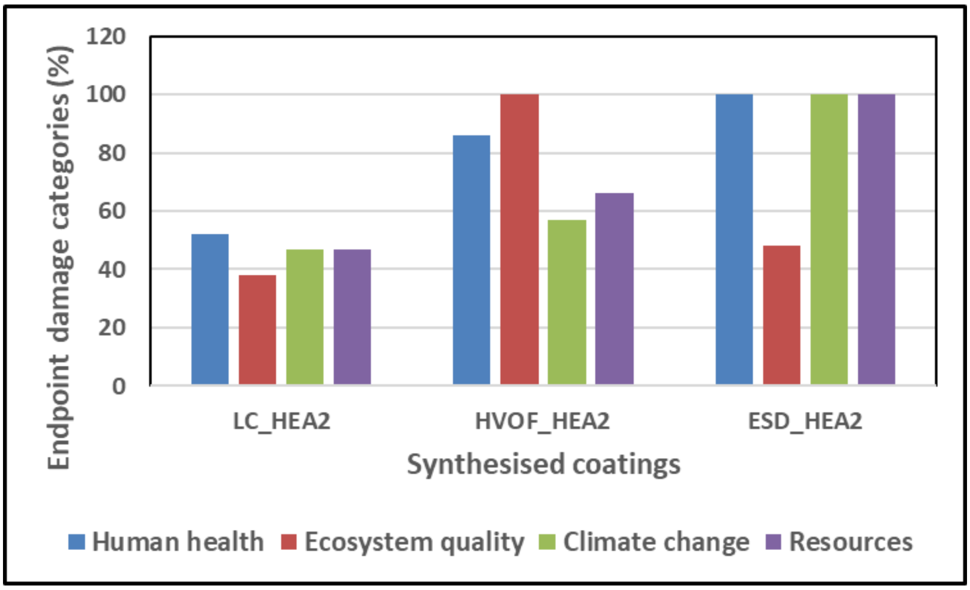

Figure 6 – A graphical presentation of the environmental impacts of the three synthesised coatings LC_HEA2, HVOF_HEA2 and ESD_HEA2 for 4 endpoint damage categories.

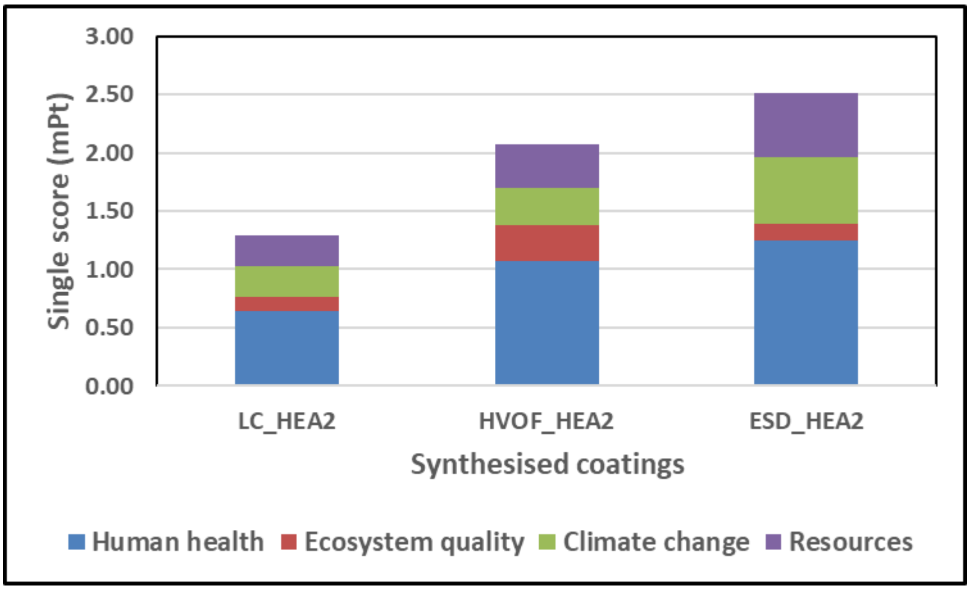

Figure 7 - Single score presentation of the environmental impacts of LC_HEA2, HVOF_HEA2 and ESD_HEA2 synthesised coatings for four endpoint damage categories.

The LCA tool calculated 15 midpoint impact and 4 endpoint damage categories for LC_HEA2, HVOF_HEA2 and ESD_HEA2 synthesised coatings each of 1 µm thick over 1 m^2 area using IMACT2002+ version 2.14 LCIA methodology. The quantification of the LCIA results for midpoint impact and endpoint damage categories of these synthesised coatings with respective units are given in Tables 14 and 15, respectively.

Table 14 - Quantification of environmental impacts of LC_HEA2, HVOF_HEA2 and ESD_HEA2 synthesised coatings over 15 midpoint impact categories.

Impact category	Unit	LC_HEA2	HVOF_HEA2	ESD_HEA2
Carcinogens	kg C_2H_3Cl eq	0.04	0.04	0.06
Non-carcinogens	kg C_2H_3Cl eq	0.17	0.19	0.21
Respiratory inorganics	kg PM2.5 eq	0.01	0.01	0.01
Ionizing radiation	Bq C-14 eq	24.16	34.70	81.73
Ozone layer depletion	kg CFC-11 eq	0.00	0.00	0.00
Respiratory organics	kg C_2H_4 eq	0.00	0.00	0.00
Aquatic ecotoxicity	kg TEG water	854.93	2049.66	1069.42
Terrestrial ecotoxicity	kg TEG soil	180.27	498.01	225.87
Terrestrial acid/nutri	kg SO_2 eq	0.07	0.12	0.11
Land occupation	m^2org.arable	0.09	0.12	0.08
Aquatic acidification	kg SO_2 eq	0.02	0.03	0.04
Aquatic eutrophication	kg PO_4 P-lim	0.01	0.03	0.01
Global warming	kg CO_2 eq	2.65	3.18	5.61
Non-renewable energy	MJ primary	36.19	45.17	80.38
Mineral extraction	MJ surplus	3.54	10.27	4.19

Table 15 – Quantification of environmental impacts of LC_HEA2, HVOF_HEA2 and ESD_HEA2 synthesised coatings over 4 endpoint damage categories

Damage category	Unit	LC_HEA2	HVOF_HEA2	ESD_HEA2
Human health	DALY	4.55×10^{-6}	7.57×10^{-6}	8.82×10^{-6}
Ecosystem quality	PDF*m2*yr	1.64	4.29	2.05
Climate change	kg CO2 eq	2.65	3.18	5.61
Resources	MJ primary	39.70	55.40	84.60

The quantified value of four endpoint damage categories have been converted to a single score value in terms of point (Pt) and listed in Table 16 including the total score values of LC_HEA2, HVOF_HEA2 and ESD_HEA2 synthesised coatings.

Table 16 - Single score values of LC_HEA2, HVOF_HEA2 and ESD_HEA2 synthesised coatings.

Damage category	Unit	LC_HEA2	HVOF_HEA2	ESD_HEA2
Total	mPt	1.29	2.07	2.52
Human health	mPt	0.64	1.07	1.24
Ecosystem quality	mPt	0.12	0.31	0.15
Climate change	mPt	0.27	0.32	0.57
Resources	mPt	0.26	0.36	0.56

From the LCIA results of LC_HEA2, HVOF_HEA2 and ESD_HEA2 synthesised coatings shown in Figures 6 and 7 and Tables 14-16, the LC_HEA2 synthesised coating showed lower environmental impacts as compared with the HVOF_HEA2 and ESD_HEA2 synthesised coatings. It is demonstrated that the laser cladding (LC) deposition process is more environmentally friendly than those of HVOF and ESD processes even though grinding surface preparation process used for LC process is about two times higher than that of grit blasting surface preparation process used before applying ESD and HVOF deposition processes.

4. CONCLUSIONS

The aim of this study was to obtain a green and sustainable Geo-Coat technology for combating the aggressive environment of medium to high temperature geothermal resources. From the LCIA results of 5 HEA coatings deposited through HVOF, LC and ESD processes, the following important points have been drawn:

- The gas-atomising method used for manufacturing HEA2 coating powder is less energy-intensive than that of the mechanical alloying method used for manufacturing HEA1, HEA3-HEA5 coating powders.
- Grinding process applied for substrate surface preparation before LC deposition requires more resources and energy than that of the grit blasting process applied before HVOF and ESD deposition processes.
- LC_HEA2 synthesised coating showed better environmental performances as compared with HVOF_HEA2 and ESD_HEA2 synthesised coatings since HVOF and ESD deposition processes generate more environmental impacts as compared with LC process due to more resource and energy consumptions.

Finally, it has been concluded that the Geo-Coat technology LC_HEA2 demonstrated lower environmental impacts as compared with other Geo-Coat technologies studied. It is worth mentioning here that LC_HEA2 Geo-Coat technology not only green and sustainable but also been demonstrated as the best candidate Geo-Coat technology for different application areas such as pipes & casings, turbine components to protect against corrosion and erosion damages [6].

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