Environmental Impact of Ship Hull Repair

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Abstract

This study presents an environmental analysis of a number of cutting and joining processes taking place during the ship hull repair. These processes include *Oxy-acetylene cutting*, *Plasma arc cutting*, *Shielded metal arc welding*, *Flux core arc welding* and *Submerged arc welding*. The processes are modelled in terms of their environmental impact. The environmental-related inputs and outputs of each process are elaborated with a Life Cycle Assessment tool. The impact on various aspects, such as human health, resource depletion etc., is assessed by the "Environmental Priority Strategy (EPS)" and the "Eco-Indicator 99" impact assessment methods. Based on the results, a benchmarking of the cutting and welding processes is performed, in terms of their environmental impact.

Keywords

Environmental, Welding, Cutting

1 INTRODUCTION

The ship hull repair is the most essential task undertaken by ship repair yards. The environmental impact of the hull repair procedure is an issue that has not been dealt with and ought to be considered seriously. Hull repair is based on two major process categories: cutting and welding. These processes are used extensively for mild or high tensile steel plates that range in thicknesses from 2 to 30 mm or more. The length of these operations can easily exceed many hundreds of meters for each repair session. Work is performed either in the controlled environment of a workshop, or on board. The most frequent processes used are Arc welding or Gas cutting and are known for their high energy requirements and dangerous fume generation.

1.1 Shielded Metal Arc Welding (SMAW)

This manually applied process uses standard length and diameter flux covered metal electrodes. An arc is created between the electrode and the workpiece, creating sufficient heat to melt both the metal in the electrode and the workpiece. Molten metal from the electrode is transferred through the arc onto the workpiece. Burning the flux creates a cloud that surrounds the arc and protects the welding area from oxidization. As the arc moves away, the molten metal freezes and solidifies and thus, fusion is performed. Electrodes are consumed and replaced after a certain amount of welding. The process parameters, which ultimately influence the environmental output, are highly dependant on the human factor.

1.2 Flux Core Arc Welding (FCAW)

This process is a variation of Gas Metal Arc welding (GMAW). Instead of standard length electrodes, as in SMAW, a metal wire along with a shielding gas is fed continuously to the welding area. The gas can be Argon, or CO₂, depending on the type of metal to be welded. FCAW differs from GMAW in that the wire is cored with flux. FCAW can be semiautomatic or automatic.

1.3 Submerged Arc Welding (SAW)

SAW is usually an automatic process that is used, as opposed to SMAW and FCAW, in the workshop and not on board a ship. This process uses a wire fed at constant speed, depending on the welding parameters and

granular flux is pre-placed on the workpiece ahead of the arc.

Figure 1: Submerged arc

1.4 Oxy-Acetylene Cutting (OAC)

In this process, a high temperature oxyacetylene gas flame is used to preheat the workpiece at a kindling temperature to which it will react rapidly with a stream of oxygen.

1.5 Plasma Arc Cutting (PAC)

PAC is a process that uses ionized gas (plasma) created by an arc for melting the metal. The process is automatic and usually the workpiece is submerged in water, which plays the role of the coolant, for less heat distortion and quieter operation [2].

A number of previous works have mostly focused on air emission measurement. An extensive report on welding fume formation is provided in [7]. In [8] several common welding processes adopted by shipyards are studied and their corresponding emission factors are developed. Sampling airborne particles in welding and allied processes is the focus of the work in [9] as well as comparison with data sheet fume composition. A model for calculating the fume formation rate of GMAW is developed in [10]. In [11] the fume formation rate in GMAW for a wide range of output currents and voltages is measured using a custom built fume chamber.

2 ENVIRONMENTAL ASSESSMENT METHODOLOGY

Environmental assessment (EA) of a process includes evaluation of the environmental, occupational health and resource consequences. It is actually a part of a product's Life Cycle Assessment (LCA). The product in this case is the ship, and the specific processes refer to the repairing part of the ship's life. In the case of the ship repair, where it is evident that the most dangerous environmental processes are cutting and welding, the EA goal has been the quantification of this danger and a benchmarking of the various different processes used.

Two major steps comprise the EA: The Inventory, which is the quantification of the process' inputs and outputs, including material and energy usage, heat and fume generation etc. and the Impact analysis, which is the qualitative and/or quantitative characterization and assessment of the environmental threats, as they have been identified in the Inventory [12].

The EA was performed with the LCA tool, SimaPro 6.0. This tool consists of databases that refer to materials, energy, transportation, manufacturing processes, use, disposal and waste treatments. The assessment methods used in this work are the Eco-Indicator 99 and the Environmental Priority Strategy (EPS) 2000.

The EA of the processes dealt with in this paper has been based on the collection of information on the process parameters, their classification as inputs and outputs and their consumption or production respectively. Indicatively, in figure 2, a flow chart describes the procedure followed for assessing environmentally the FCAW process.

Figure 2: Environmental assessment procedure for FCAW

3 PROCESS INVENTORY

The various cutting and welding processes have many different parameters that are set according to the type of weld, the orientation, the angle among the components to be joined, the material properties, the thickness of the components etc. Depending on these characteristics, edge preparation is defined (for welding), along with the speed of the process, the thickness of electrodes-wires, the wire or gas feed rate etc.

In this work, the cutting and welding has been performed on a 12mm thick high tensile steel ship hull plate. A simple butt weld has been examined for all the different processes, in order for a clearer benchmarking to be achieved. This type of workpiece and weld type have been chosen, because they are amongst the most common cases in shiprepair. The qualitative results of

this work should apply to different types of welds for the same cutting and welding processes. Data on the process parameters have been obtained empirically from the ship repair yards. Electrode material, fume generation rate and fume composition for each process have been acquired from [3-11]. All parameters have been estimated for 1 meter of cutting or welding. Table 1 and 2 show the process parameters for each method.

It should be mentioned that secondary operations, such as scrap production, transportation of resources, surface cleaning and painting, etc. have not been taken under consideration. This work has been focused on the environmental modeling of the processes themselves.

	SMAW	FCAW	SAW
Welding speed (m/h)	12	15	41.4
Machine energy consumption (KW)	6.5	3.61	13.3
Electrode length (mm)	450	n/a	n/a
Electrode/wire diameter (mm)	5	1.2	5
% of flux in electrode volume	50	n/a	n/a
Shielding gas consumption (kg CO ₂ /kg of wire)	n/a	4.5	n/a
Flux rate (kg/meter of wire)	n/a	n/a	1.62

Table 1: Welding process parameters

	OAC	PAC
Cutting speed (m/h)	19.8	40
Machine energy consumption (KW)	n/a	16
Oxygen supply (m ³ /min)	0.0708	n/a
Acetylene supply (m ³ /min)	0.0085	n/a
Electrode length (mm)	n/a	40
Electrode thickness (mm)	n/a	10
Electrode feed rate (electrodes/m of cut)	n/a	1/300
Shielding gas (Ar) flow rate (m ³ /m of cut)	n/a	0.0378

Table 2: Cutting process parameters

The edge preparation is shown in figure 3 for each one of the welding processes. According to the corresponding edge preparation, consumption of electrode or wire and heat transfer has been approximated by the volume of material that must be added in order for the fusion to take place.

Figure 3: Welding process edge preparation

In tables 3 and 4 are shown the chemical compositions of electrodes and wires for the processes under study.

Wire	%	Flux	%
C	0.14	TiO ₂	43.5
Mn	0.6	CaF ₂	6
Si	0.1	CaCO ₃	21.5
S	0.3	Mica	10.4
P	0.3	Fe-Cr	12
Fe	98.54	Feldspar	6.6

Table 3: AWS E71T-11 electrode chemical composition (SMAW) [6]

Wire	%	Flux	%
C	0.14	CaO	25
Mn	0.6	MgO	35
Si	0.1	SiO ₂	15
S	0.3	CaF ₂	25
P	0.3		
Fe	98.56		

Table 4: FCAW and SAW wire-flux chemical composition [6]

Substance	%
Cu	75
Mn	13
Ni	2.3
Fe	2.2
Al	7.5

Table 5: PAC electrode chemical composition [6]

According to the electrode, wire and/or gases chemical composition, feed rate, total amount (approximated on edge preparation and/or process speed) and density, the mass of each substance has been calculated for one meter of cutting or welding, denoted as specific mass. These amounts were later fed as inputs from nature (raw materials etc.) and/or technosphere (electricity, transport etc.) into the LCA tool. The same procedure has been followed for the determination of fumes (air emissions) of the processes. Tables 6 and 7 show the fume formation rates and their chemical composition for the welding processes.

	SMAW	FCAW	SAW
Fe	15	17	-
Mn	7	7	-
Si	9	5	-
Ca	5	2	-
K	15	19	-
Na	10	6	-
F	17	22	-
Mg	-	4	-
Ni	6	4	52
Cr(VI)	6	5	2
Cr(total)	10	9	46

Table 7: Welding process fume composition [5]

Process	Fume formation rate (gr/min)
SMAW	0.5625
FCAW	0.3
SAW	0.005

Table 6: Welding process fume formation rates [5]

An alternative way of calculating the emissions is through the Emission factor equation [3]:

$$E = W * PC * EF * CF, \text{ where}$$

W: weight of electrode per meter of cut/weld (gr)

EF: emission factor (lb/ton)

CF: constant factor (ton/lb)

PC: percentage composition of material

The Energy and Heat produced were also the input for the environmental assessment of these processes. Energy has been calculated according to the machine's power and time of welding/cutting, determined from the process speed for 1 meter of cutting/welding. The heat produced for metal fusion (welding) or melting (cutting) has been calculated as follows:

$$H = \int_{T_0}^{T_m} K_t(T) A t \frac{dT}{d}, \text{ where}$$

K_t: thermal conductivity of metal

A: area of heat transfer (approximated according to edge preparation)

T_m: melting/fusing temperature

T₀: reference temperature

d: thickness of molten/fused metal (thickness of plate)

t: time of process (calculated from process speed for 1 meter of cutting/welding)

In table 8 the heat calculated for the studied processes is shown.

Process	Heat (KJ)
SMAW	813.74
FCAW	1329.1
SAW	678.46
OAC	86.076
PAC	169.53

Table 8: Heat produced for 1 meter of cutting/welding

4 ENVIRONMENTAL ASSESSMENT

The inputs from nature or the technosphere, and the outputs as air emissions have been fed into the LCA tool. Using two methods of assessment (Eco-indicator and EPS), evaluation of the environmental damage have taken place. More than 600 different substances, either raw materials or emissions to air, water and soil have been calculated for each one of the processes. Part of the quantitative environmental assessment results is presented in table 9, where a small part of the inventory for the welding processes is included. This is useful in order to have a direct reference to the various material usage and emissions for each process.

No	Substance	Un.	SMAW	FCAW	SAW
309	Methanol	mg	101	335	0.794
310	Molybdenum	mg	2.8	1.58	0.0332
311	Monoethanolamine	µg	208	317	4.08
312	Neptunium-237	nBq	4.72	15	2.27
313	Nickel	g	0.39	0.75	3.77
314	Niobium-95	µBq	2.94	8.09	0.993
315	Nitrate	mg	2.81	0.114	0.0064
316	Nitrogen	mg	35.1	14.4	2.77
317	Nitrogen oxides	g	734	374	4.2

Table 9: Welding process Inventory part

The qualitative results from the assessment are presented in the following charts (figures 4-7 and 10). The two methods for environmental assessment cover different impact sectors. Figures 4 to 7 show the amount of environmental damage in the main impact sectors, which are:

- Human health,
- Ecosystem quality and
- Resources

for Eco-Indicator 99, and

- Human health,
- Ecosystem production capacity,
- Abiotic stock resource and
- Biodiversity

for EPS 2000.

The environmental inputs and outputs of the processes dealt with have been categorized in the corresponding impact sector, as per the given methodology (e.g. Eco-indicator or EPS). The amounts of these inputs and outputs determine the extent of environmental damage, which is represented in points (Pts) in the charts. These points express the relative damage of the processes compared.

Figure 4: Cutting processes impact assessment (weighting) chart according to Eco-indicator 99

Figure 5: Cutting processes impact assessment (weighting) chart according to EPS 2000

Figure 6: Welding processes impact assessment (weighting) chart according to Eco-indicator 99

Figure 7: Welding processes impact assessment (weighting) chart according to EPS 2000

Figure 8 lists the detailed impact categories and their relation to the main sectors according to the two EA methods:

Figure 8: Eco-Indicator 99 impact categories

Figure 9: EPS 2000 impact categories

The results depicted in figures 4-7 have derived from the amount of damage inflicted per impact category for each sector (e.g. in Eco-Indicator, the sum of Land Use, Fossil fuels and Minerals damage gives the damage in Resources). In figure 10 the detailed damage assessment is presented per impact category for the welding processes, according to the Eco-Indicator. The graph is presented in a logarithmic scale, because the difference in certain impact categories' values among the processes is more than two orders of magnitude.

Figure 10: Welding processes impact assessment (normalization) logarithmic chart per impact category, according to Eco-Indicator 99

5 ANALYSIS OF RESULTS

In the figures it is clear that the automatic processes (SAW and PAC), as expected, are far more environmentally friendly than the manual ones (SMAW, FCAW and OAC). According to the Eco-indicator, among the welding methods FCAW is 70% more hazardous when compared with SMAW. The impact on the human health is the factor that sets this process as the most dangerous one. According to EPS, FCAW is twice as dangerous as SMAW, mainly due to SMAW's impact on abiotic stock resource. SAW is considered having insignificant impact compared with the manual processes of both EA methods.

As far as the cutting processes are concerned, OAC is two orders of magnitude more dangerous than PAC is

according to the Eco-Indicator, but based on the EPS method, PAC has a greater impact on the abiotic stock resources and therefore, it is considered more dangerous overall.

Figure 10 provides a more detailed view of the welding processes' impact on all impact categories as described by the Eco-Indicator. Here, it can be seen that Carcinogens is the most influenced impact category that makes FCAW stand out as the most dangerous process. Respiratory inorganics is also a greatly influenced category for the specific process, whereas, in other categories FCAW is considered fair. In fact, SMAW has a greater impact on Fossil fuels than it does on the other two processes.

The Carcinogens and Respiratory Inorganics great impact of the FCAW is most probably due to the high fume formation (Chromium and Nickel). Although the FCAW has a lower fume formation rate than the SMAW does, the total fume mass generated is greater. This is mainly because the edge preparation for the FCAW requires more material per cross section of the weld to be added. For the particular application, the FCAW is operated longer and therefore, it produces more fumes.

PAC is an automated process with very low fume formation and consumable usage (1 electrode per 300 meters of cutting). Also, although it has the greatest power consumption, due to its high speed, the total energy consumption is relatively low. The OAC's greater impact, mainly on human health, is due to the consumption of oxygene and acetylene.

Of course, the results presented, stand only for a specific case of cutting or welding. It has been also assumed that the process parameters, which are highly dependant on the welder's skills, are constant and are supplied by the ship repair yards, according to their experience. Therefore, it is possible that in other cases, when dealing with different welders and different applications the results will be varying.

6 CONCLUSIONS

This report is a preliminary qualitative and quantitative comparison of various processes of cutting and joining, used in the ship repair industry, from an environmental point of view. Summarizing, the following conclusions can be derived:

- FCAW and OAC are the most environmentally unfriendly processes among the welding and the cutting processes respectively.
- According to the EPS 2000, the FCAW mostly influences human health (approximately 85% more than SMAW).
- According to the EPS 2000, the SMAW has greater influence on resource depletion (approximately 50% more than FCAW).
- OAC has been found to be far more hazardous than PAC according to the Eco-Indicator, both on Human health and on Resources sectors, but the EPS 2000 has defined PAC as the most dangerous in Abiotic stock resource, which makes it more environmentally unfriendly overall. The difference in results is due to the method's different approach as to the importance of each environmental effect.
- Automatic processes are, as expected, more environmentally friendly. Especially SAW is

considered having insignificant effect on the environment when compared with the other manual processes, such as SMAW and FCAW. However, the usage of automatically controlled cutting and welding processes is limited to the workshop and cannot easily be applied on board, where a great variety of welding positions, types and conditions is met.

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