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Ecological and Energetical Characteristics of the Friction Stir Welding Process

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Abstract

The ecological welding processes must have the emissions of greenhouse gases (carbon dioxide, nitric dioxide), polluting substances (lead, mercury, cadmium e.a.), welding fumes and gases below the allowed limits. The friction stir welding (FSW) process is ecological, because the emission level is zero.

In the case of the experiments for welding 4...6 mm thick aluminum plates, the specific electric energy consumption of the FSW process is 0.08711 ...0.11083 kWh/m, less than the consumption of the gas metal arc welding process, by the difference ΔE = 0.01746 ... 0.08329 kWh/m.

Keywords: *friction stir welding, ecological characteristics, zero emissions, energy characteristics, reduced electric energy consumption.*

Introduction

The ecological welding processes must comply with the technical requirements concerning the environment protection and labor health, according to the ISO 9000, ISO 14001 and ISO 18001 standards regarding the integrated management system of quality, environmental protection, occupational health and safety, as well as the standards of these domains [1, 2].

In the first place, the emissions of greenhouse gases (carbon dioxide, nitric dioxide) and polluting substances must be reduced to a minimum or eliminated, for the purpose of the environment protection.

Secondly, the concentrations measured in the breathing air at the work place, of the hazardous and poisoning substances exhaled during the welding and allied processes, must be reduced below the allowed limits, in order to assure the occupational health and safety conditions for the working personnel.

Reducing the energy consumption has savings effects, but there is also an indirect ecological effect, by reducing the share of emissions of greenhouse gases and polluting substances of the electrical energy production using the present conventional processes, which refers to the energy consumption of the welding process [1, 2].

Theoretical and Experimental Details

The gases and particle substances produced by the welding, cutting and allied processes are classified as follows, by the effects upon the organism [3, 4]:

A. Hazardous gases: carbon dioxide; argon; helium; oxygen; gases exhaled from the coating materials: carbon monoxide, formaldehyde (oxymethylene), polyurethane toluene, hydrocyanic acid, phosgene, e.a.

B. Hazardous particles: chromium VI, nickel, copper, lead, zinc, iron and aluminium oxides, as fume or dust.

C. Poisonous gases: carbon monoxide; nitric oxides; ozone.

D. Welding fumes are suspensions of very small-size solid-microparticles (iron, manganese, chromium and nickel), that can affect mainly the breathing system.

In the table 1, the main noxious substances exhaled by welding, with their main harmful effects upon environment and health are presented [3-7].

Table 1. Noxious substances exhaled by welding and their effects

No.	Name of the substance	Main effects upon environment and health
1.	Carbon Monoxide CO	Tissue hypoxia; headache; weakness, irritability; nausea; flushing; weakness; unconsciousness; heart stop; death
2.	Nitric Dioxide NO_2	*Greenhouse gas*; dyspnea; difficult breathing, throat spasms; asphyxia; genetic mutations; fatal edema; death
3.	Nitric Oxide NO	Affects central nervous system; cardiovascular, hepatic, hematopoietic, and reproductive effects
4.	Ozone O_3	Irritates upper breathing tract; pulmonary edema; bronchitis; asthma; lung function growth; lung cancer
5.	Phosgene CCl_2O	Acute lung damage/edema; cumulative lung damage-emphysema; fibrosis; eye irritation; dyspnea
6.	Fumes, total content	Affects mostly lungs; potential occupational carcinogens; benign pneumoconiosis; arc welder's siderosis
7.	Fumes, from stainless steel	Contain CrVI and Ni; cancer
8.	Hexavalent Chromium CrVI	Dermatitis; chrome ulcers; crusted skin sores; burning sensation, nosebleeds; nasal perforation; lung cancer
9.	Trivalent Chromium CrIII	Effect on skin, liver, kidneys; dermatitis; carcinogenic
10.	Beryllium Be and compounds	Respiratory illness similar to pneumonia or bronchitis; carcinogens; chronic beryllium disease; death
11.	Cadmium Cd and Cadmium Oxide CdO	Acute pulmonary edema; kidney damage, excretion of excessive protein; cancer (lung and prostate); carginogens; death from asphyxia
12.	Cobalt Co and compounds	Interstitial fibrosis and pneumonitis; myocardial and thyroid disorders; asthma attack; wheezing; dyspnea
13.	Nickel Ni , insoluble compounds	Heart and respiratory disorders; birth defects; asthma; lung embolism; carcinogens; lung, nose, larynx cancer
14.	Fluoride	Irritate the eyes, nose, and throat; pulmonary edema; bone damage ; skin rashes
15.	Iron Oxide Fe_2O_3	Pulmonary inflammation; lung changes, siderosis, fibrotic pneumoconiosis; metal fume fever
16.	Manganese Mn ; inorganic compounds	Cumulative central nervous system, lung, kidneys damage; pneumonia; asthenia; insomnia; anorexia

17.	Copper Cu	Lung damage/edema; eye, upper respiratory tract irritation; dermatitis; metallic taste; metal fume fever
18.	Lead Pb	Saturnism; affects the brain, central nervous system, circulatory, reproductive system, kidneys, muscles; disruption of haemoglobin biosynthesis; anemia; weakness
19.	Mercury Hg	Effects in the central and peripheral nervous systems, lungs, kidneys, skin and eyes; dyspnea; general malaise
20.	Carbon Dioxide CO_2	*Greenhouse gas*; toxic by reducing the oxygen content of the breathing air, in limited locations
21.	Argon	Inert gas; asphixia by reducing the oxygen content of the breathing air, in closed locations

According to some preliminary estimations, the joining processes that are ecologic, because they comply with the requirements regarding the emissions of greenhouse gases and poisoning substances are the following: friction stir welding (FSW), laser welding and ultrasonics welding. The supply based on solar energy of certain welding equipment is possible and also ecological, because it reduces the share of the polluting emissions that arise from the energy consumption [8].

The principle of the FSW process is the following: the rotating welding tool is introduced between the two plates and it is moved along the jonction line, making a welded joint, by stirring and mixing the base metal of both plates [3-5].

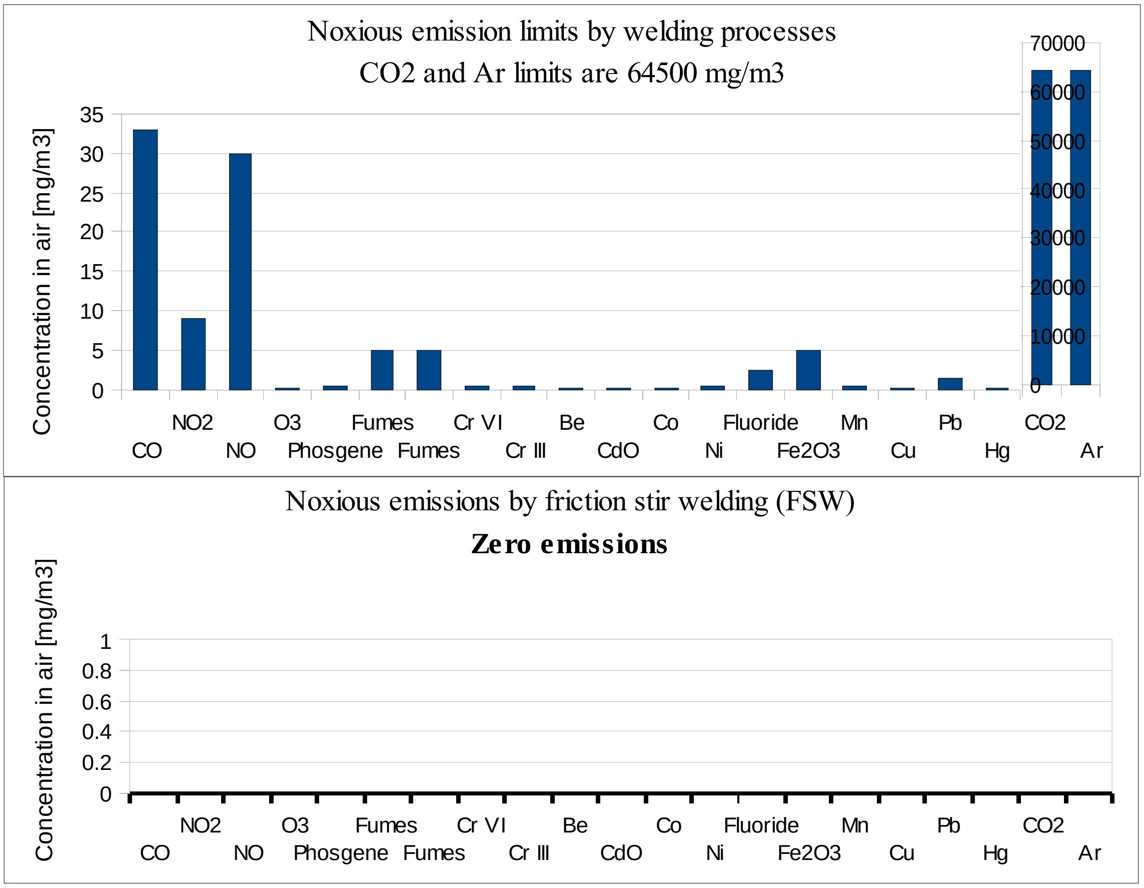

Fig. 1. Limits of noxious substances exhaled by welding processes, compared to FSW

Ecological characteristics

A comparison between the ecological characteristics of the gas metal arc, gas tungsten arc and friction stir welding is described below. The FSW process has the *essential ecological advantages* of completely eliminating the following factors: ultraviolet radiation, carbon dioxide, carbon monoxide and nitric oxides emissions, argon emanation, other noxious gases and fumes exhalations. The quantitative evaluation of the share of these eliminations in the total amount of the counteracting measures against the global warming phenomenon and polluting process must take into account the balance of the welding operations in the total of the present industrial technologies.

Some exposure limits (8 hours a day, 5 days a week) or the maximum allowed concentrations of the noxious emissions in the tidal air at the work place for the classic welding processes are presented in fig.1, compared to FSW. The complete exclusion of these substances allowes the FSW to be classified as a process with zero emissions of polluting substances. Thus, the FSW process has a maximal contribution in reducing the pollution and the global warming.

By replacing the gas metal arc welding with the FSW process in the fabrication of some railway structures, a company mentions a 25000 kWh reduction of the energy consumption for 96000 m of weldments, which means 0.26 kWh/m reduction. Besides, the elimination of the filler metals, reduction of the transportation and labor costs are mentioned, as the machining of the workpieces is not needed before or after the welding process [3, 4]. Another company reports about eliminating 26100 litres argon consumption in the fabrication of some aluminium structures, as a consequence of replacing the gas metal arc welding with the FSW process [3].

Main properties

The process is most suitable for components which are flat and long (plates and sheets) but can be adapted for pipes, hollow sections and positional welding. The welds are created by the combined action of frictional heating and mechanical deformation due to a rotating tool. The maximum temperature reached is of the order of 0.8 of the melting temperature [1].

The two halves to be joined must be rigidly fixed before the welding operation. The pin, which is an integral part of the tool, is plunged into the metal to help stir it up; the shoulder of the tool generates much of the heat. As the weld is completed, the tool is withdrawn, leaving behind a hole. The weld is designed so that such regions can be discarded from the component. The presence of a hole may not be appropriate when welding pipes or storage vessels. The hole can be avoided by designing the tool such that only the pin can be retracted automatically and gently into the shoulder, leaving behind an integral weld.

Since the tool gets red hot, it is necessary to protect it against the enviroment using a shielding gas. In the case of welding interstitial-free steel plates, it takes a while before the plate becomes sufficiently heated to proceed with welding.

A possible use of FSW in the welding of stainless steels [1]. Chemical segregation effects associated with welding processes involving solidification are avoided. Such segregation can lead to a degradation of corrosion resistance since electrochemical cells are set up between solute-rich and poor domains.

Processing variables and welding parameters

Joint profiles, microstructures and properties are governed by the thickness and material kind of the stock being welded and by choice of processing variables. Processing variables include the weld parameters (speeds, tilt, etc.), tool design (configuration and materials) and, in butt joints, even material and thickness of the back plate.

A multitude of welding parameters are considered at the FSW process [1, 2]: rotational speed (rpm), travel speed, normal force, lateral force, tool attitude (tilt angle), shoulder plunge, penetration ligament (butt joints), penetration into the bottom member (lap joints). Welding parameters are generally considered proprietary and, as such, are often fully or partially restricted from publication. Of those publications that disclose some weld parameters, only a handful mentions penetration ligament, shoulder plunge or tilt. The most widely disclosed and investigated parameters are the rotational and travel speeds. In general, slower travel speeds and lower rotational speeds are used for harder alloys or thicker sections. Increasing the rotational speed or decreasing travel speeds tends to increase heat input and welding temperatures. However, extremely high or low travel and rotational speeds can adversely affect properties. Nevertheless, the quest for increased travel speeds is relentless, due to economic pressures. The travel speeds quoted in this document do not exceed 1300 mm / min. It is said, however, that machines capable of up to 2540 mm / min are available on the market. In practice, weld parameters have to be adapted / optimized for the particular alloy type and condition / heat treatment, thickness of the stock being welded and the type of joint being produced.

Welding equipment

Friction stir welding is a fully mechanized process [2]. The forces generated by the process are high enough that handheld operation is not possible, except possibly for very thin materials, so the workpiece is generally constrained by a welding fixture during welding. This makes the equipment cost much higher for FSW than for most traditional fusion welding processes, but the labor cost is generally lower and the weld quality is much more consistent. Although equipment cost is certainly a barrier to widespread use of the process, the reduction in the need for skilled labor is a large selling point for the process, especially in the shipyard setting where maintaining skilled labor can be a challenge. The high cost of FSW equipment and the relative new aspects of the process make it impractical for most shipyards to establish and maintain an in-house capability, but there are two FSW service providers that can construct FSW weldments and transport them to shipyards.

The traditional method of stiffening bulkheads, decks, and hulls is to use arc welding techniques to fillet weld extruded shapes to plate materials. Since FSW produces lower distortion in most welding situations, there is no need to avoid butt welds, and since the process is fully mechanized, labor cost is minimized. As a result, the optimum method for FSW construction is to butt weld extruded shapes to build up stiffened panels. It can be done as a pre-fabricated subassembly, then cut to fit as required for installation. The utility of pre-fabricating integrally stiffened panels should not be underestimated. Shipyards often have difficulty maintaining staff for arc welding aluminum due to the skill required to manually make high-quality welds. If generic panels can be purchased from a subcontractor or fabricated in-house on an automated machine, there can be a significant reduction in the amount of manual welding that must be carried out. This reduces labor costs, reduces staffing requirements, and if planned correctly, reduces the time that a ship under construction is occupying floorspace.

Results

Based on its own experimental data, at ISIM of Timisoara, a comparative estimation of the specific electric energy consumption of both the gas metal arc and friction stir welding processes was made [8]. Some welding data of the previous and recent experiments performed on a custom-made FSW equipment [4] were considered.

The operation principle of the FSW process needs two main technological movements: the rotation of the tool and the travel along the joint line. Thus, the specific energy consumption of the FSW process is given by the equation [8]:

$$E = (k1 \cdot P1 + k2 \cdot P2) \cdot n / v_s \quad (1)$$

In the above relationship P1 = 4.0 kW is the rated power of the electric motor for the rotating function, P2 = 2.2kW is the rated power of the electric motor for the travel function. As the motors are not permanently under load at the rated extent, the power quantities must be adjusted by means of the loading factors k1 = 0.10 ...0.60 and k2 =0.12...0.65, which are assessed by monitoring the parameters during the welding process. The number of passes is n = 1 (max.2, on both sides). The quantity v_s= 0.10 ...0.15m/min = 6 ...9m/h is the welding speed.

The specific electric energy consumption of the FSW process, related to one meter weld, is in the range 0.08711...0.11083 kWh/m [8], in the case of welding some 4...6 mm thick aluminum plates. It has to be noticed that with increasing speed the specific consumption is less. Therefore it is an advantage to use high welding speed. This advantage is applied in the industrial activity of certain companies that use successfully the FSW process. For other materials, other thickness values and other welding data, the extent of the energy consumption is different. In the case of a high strength alloy, if the welding speed is low, the energy consumption of the FSW process may even exceed the consumption of the gas metal arc welding process.

In the case of the gas metal arc welding (GMAW) process, the specific electric energy consumption per one meter of weld is computed using the next relationship [8]:

$$E = (U_a \cdot I_s \cdot 10^{-3} / \eta) \cdot n / v_s \quad (2)$$

In the relationship (2), U_a = 20V...23V is the electric arc voltage; I_s = 80A...120A is the welding current; the factor 10^{-3} is introduced in order to obtain the electric energy consumption expressed in the measuring unit kilowatt· hour/ meter; η = 85%/100% = 0.85 is the efficiency of the welding source; n = 1 (max. 2) is the number of passes; v_s = 0.20 ...0.30m/min = 12.0...18.0m/h is the welding speed.

The specific electric energy consumption of the gas metal arc welding process is in the range 0.10457... 0.19412 kWh/m [8], in the case of welding 4...6 mm thick aliminum plates.

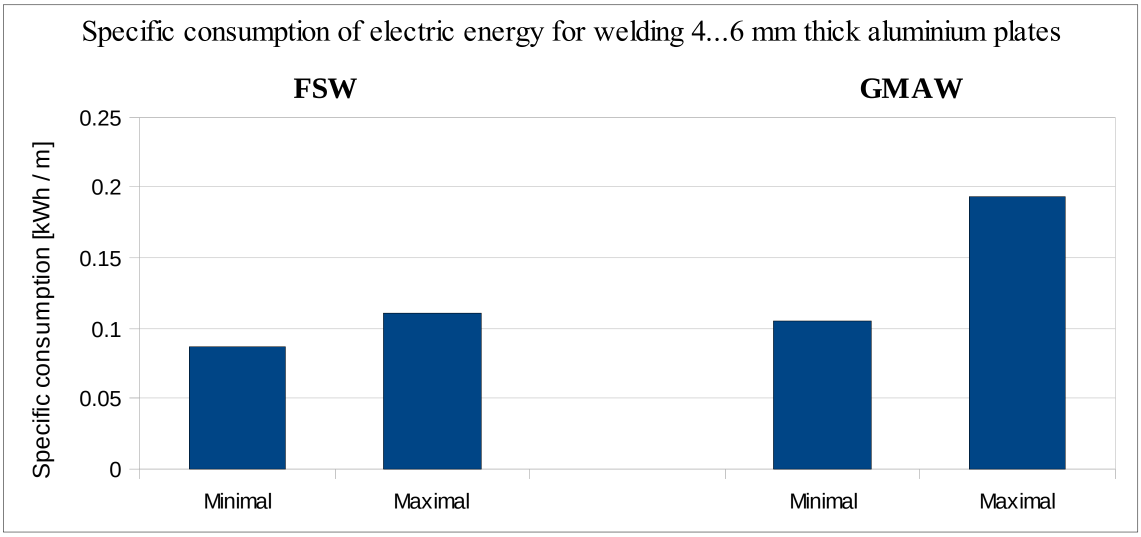

Fig. 2. Specific electric energy consumption of the FSW and GMAW processes

In fig. 2 the extents of the specific electric energy consumption of both the friction stir welding (FSW) and gas metal arc welding (GMAW) processes are compared.

The difference between the specific consumption of electric energy of the two processes is in the range ΔE = 0.01746 ... 0.08329 kWh/m [8]. The FSW process has a reduction of the specific consumption, by the calculated difference, compared to the gas metal arc welding process, under the mentioned conditions, as shown in fig. 3.

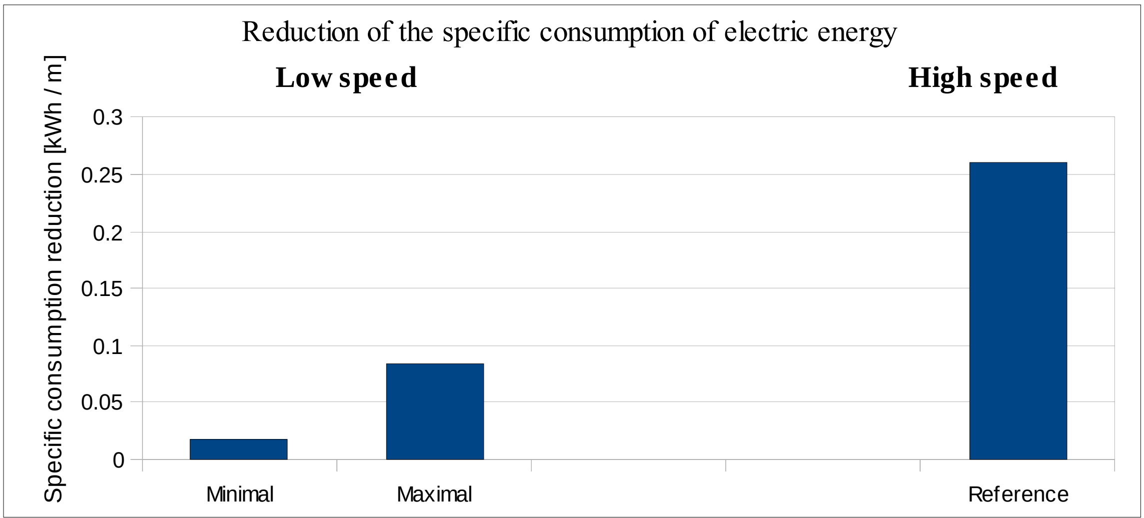

Fig. 3. Reduction of the specific consumption of the FSW related to GMAW

A 0.26 kWh/m reduction of the specific energy consumption, by replacing the gas metal arc welding with the FSW process, as mentioned in the literature [3, 4] is possible with high welding speed, which has also the advantage of reducing the total working time and other fabrication expenses of the welding technology.

Conclusions

1. The implementation in the industrial activity of certain ecological welding processes requires an ecological approach of contriving the technological processes, components, operation and use of the welding equipment.

2. The technical requirements for the ecological welding processes consist in complying with the standards and recommendations regarding both the environment protection and occupational health. The emissions of greenhouse gases (carbon dioxide, nitric dioxide), polluting substances (cadmium, mercury, lead e.a.), noxious and toxic substances at the work places must be reduced under the allowed limits.

3. The noxious and toxic substances exhaled by welding are classified as follows: *hazardous gases* (carbon dioxide, argon, helium, oxygen e.a.); *hazardous particles* (chromium VI, nickel, copper, lead zinc, iron and aluminum oxides - all as fume or dust); *poisonous gases* (carbon monoxide, nitric oxides, ozone e.a.); *welding fumes* (solid microparticles of iron, manganese, chromium and nickel e.a.)

4. The friction stir welding (FSW) is promoted as an ecological process, based on its properties: zero emissions of greenhouse gases and polluting substances; complete absence of the ultraviolet radiation; total absence of the shielding gases argon and carbon dioxide.

5. By replacing the gas metal arc with the FSW process in the fabrication of the railway carriage frames, the electric energy consumption was reduced by 0.26 kWh/m. Very large quantities of filler metals, shielding gases, auxiliary materials are also eliminated, transportation

and labor expenses are lowered, because the machining is not needed. These savings cause also an indirect reduction of the energy consumption by means of applying the FSW process.

6. In the experiments performed at ISIM of Timisoara, by welding 4...6 mm thick aluminum plates, the FSW process has reduced the energy consumption by 0.01746 ... 0.08329 kWh/m, compared to the gas metal arc welding.

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Caracteristici ecologice şi energetice ale procesului de sudare prin frecare cu element activ rotitor

Rezumat

La procesele ecologice de sudare, emisiile de gaze cu efect de seră (dioxid de carbon, dioxid de azot), de substanțe poluante (plumb, mercur, cadmiu, etc.), de gaze şi fumuri trebuie să fie mai reduse decât concentrațiile admisibile. Procesul de sudare prin frecare cu element activ rotitor (FSW) este ecologic, deoarece nivelul de emisii este zero.

În cazul experimentărilor de sudare a unor table de 4...6 mm grosime din aluminiu, consumul specific de energie electrică la procesul FSW este 0,08711...0,11083kWh/m, mai redus cu diferența ΔE = 0,01746 ... 0,08329 kWh/m, față de procesul MIG/MAG.