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Sustainability analysis of friction stir welding of AA5754 sheets

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Abstract

The environmental impact of friction stir welding process vs. welding parameters was evaluated and analysed in detail. To this purpose, butt joints in AA5754 aluminum alloy sheets were obtained at different rotational and welding speeds. All input and output data, in terms of materials, energies and emissions, were collected and analyzed using a life cycle assessment software in order to evaluate the environmental impact index. Sound weld was used as functional unit and all energy and material flows were based on it. The results given by the life cycle assessment analysis has shown that the environmental impact of friction stir welding is strongly affected by rotational and welding speeds. The environmental impact was also related to the mechanical properties of joints, expressed as ultimate tensile strength and ultimate elongation.

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Keywords: environmental impact; sustainable manufacturing; friction stir welding; life cycle assessment; aluminium alloy

1. Introduction

The industrial sector is responsible for around one forth of the total energy consumption in Europe [1]. In recent years, a trend towards environmentally benign manufacturing is emerging mainly owing to more stringent regulatory mandates and competitive economic advantages [2]. Discrete part manufacturing processes are still not well documented in terms of their environmental impact [3]. As a consequence, environmental optimisation measures are often not recognized and improved machine tool design in terms of ecological footprint reduction has only been targeted for few common processes. Furthermore, the current trend towards more energy intensive, processes is expected to enlarge the environmental impact of manufacturing.

The environmental impact (EI) of discrete part manufacturing processes can be predicted by the life cycle assessment (LCA) [4]. The LCA methods can be also used to define environmental improvement measures at machine tool as well as process condition levels [5].

As far as welding of metal alloys is concerned, friction stir welding (FSW) is receiving growing interest owing to the energy efficiency, environment friendliness and versatility that make FSW a promisingly ecologic and "green" technology [6, 7]. It is thought that friction stir welding consumes less energy as it is compared to the fusion welding technologies, due to the lower temperatures involved and the solid state nature of the process. Furthermore, FSW leads to a decrease in material waste and allows to avoid radiations and dangerous fumes.

Most of studies on FSW available in literature deals with the influence of the process parameters and tool geometry on the mechanical properties, microstructure and formability of both similar and dissimilar friction stir welded joints in aluminium and magnesium alloys [6, 8-12]. Despite of the interest in environmental issues related to welding processes, few data are available on the environmental impact of friction stir welding as a function of the rotational (ω) and welding (v) speeds. They have a strong influence on the joint quality and could affect the environmental impact of FSW. In particular, the rotational speed, resulting in stirring and mixing of material around the rotating pin, strongly affects the heat generation and the temperature field into the workpiece. As far as the welding speed is concerned, it moves the stirred material from the front to the back of the pin and finishes

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welding process and its value is related to the specific thermal contribution conferred to the joint [9].

In such context, the present work deals with an environmental impact analysis of friction stir welding of AA5754 aluminum alloy sheets performed under different values of welding parameters. To this purpose, butt joints were obtained using a machining center and the input and output data of the welding process, in terms of materials, energy and emissions, were collected and analyzed using a LCA software in order to evaluate the environmental impact. Finally, the EI was related to the mechanical properties of joints.

2. Experimental procedures and LCA methodology

2.1. Friction stir welding experiments

Butt joints in AA5754 aluminium alloy were obtained by FSW experiments carried out on a machining center (Fig. 1a). Sheet blanks 185 mm in lenght, 80 mm in width and 2 mm thick were used. The pin tool, in H13 tool steel, was characterised by a shoulder diameter of 12 mm, a truncated cone pin with base diameter and an height of 3.5 and 1.8 mm, respectively (Fig. 1b). FSW was carried out with constant rotational speed equal to 1200, 1500, 2000 and 2500 rpm, and welding speed of 30, 60 and 100 mm/min. A nuting angle of 2° and a tool sinking of 0.2 mm were used.

The machining center was equipped with an electricity meter for metering of electrical energy absorbed during FSW.

a) b)

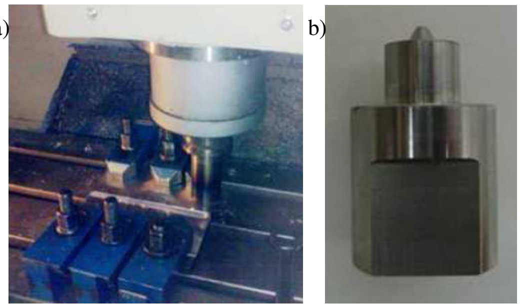


Fig. 1. (a) Friction stir welding process and (b) pin tool

2.2. Tensile tests

The mechanical properties of FSWed joints were evaluated by means of tensile tests performed at room temperature on a servo-hydraulic testing machine. Samples were machined from joints with tensile axis perpendicular to the welding line [11]. The results were plotted as nominal stress (s) vs. nominal strain (e) curves, by which the ultimate tensile strength (UTS) and ultimate elongation (UE) were derived. At least three repetitions for each testing condition were performed in order to take into account the experimental scatter.

2.3. Life Cycle Assessment

The LCA is a systematic set of procedures for compiling and examining the inputs and outputs of materials and energy and the associated environmental impacts directly attributable to the functioning of a product or service system throughout its life cycle (ISO 14040.2 Draft: Life Cycle Assessment - Principles and Guidelines). Life-cycle assessment has emerged as a valuable decision-support tool for both policy makers and industry in assessing the cradle to grave impacts of a product or process. There are four linked components of LCA. The goal definition and scoping identifies the LCA purpose and the expected products of the study; it also determines the boundaries and assumptions based upon the goal definition. The life-cycle inventory quantifies the energy and raw material inputs, and environmental releases associated with each stage of production. The impact analysis assesses the impacts on human health and the environment associated with energy and raw material inputs, and environmental releases quantified by the inventory. Finally, the improvement analysis is used to evaluate opportunities for reducing energy, material inputs, or environmental impacts at each stage of the product life-cycle.

2.3.1 Goal definition and scoping

This activity aims at investigating, from the environmental point of view, friction stir welding process of AA5754 aluminum alloy sheets. A sound weld, realised by assembling two blanks with the dimensions reported in the paragraph 2.1, has been used as functional unit and all energy and material flows are based on it. Regarding the system boundaries, the analysis did not take into account the raw material transportation up to the welding plant and the further production steps of the assembled sheets. Welding machine fulfillment was also kept out from the investigation. Since the scope of the study focuses on the defined welding product systems, other related processes were excluded from the system boundary, such as other phases of the production cycle (e.g., handling, fixturing) and equipment related processes (e.g., maintenance).

The life cycle impact assessment and the compilation of the life cycle inventory were performed using Simapro 7.3 software and ecoinvent V3 database, respectively. The data for the life cycle inventory originates from primary and secondary ones.

2.3.2 Life Cycle Inventory

The system boundary identifies the flow of energy, materials and substances that belong to the boundaries. These are the environmental aspects to be quantified in the Life Cycle Inventory (LCI). The environmental aspects can be considered as inputs to or outputs flowing from the system [13]. The main inputs of the FSW are related to the electrical energy absorbed by the machining center during welding and oil used to lubricate the different parts of the machine tool. At this stage of the work, the influence of the process parameters on the pin tool wear has been neglected since it is yet under investigation. In particular, the electrical energy consumption has been measured using an electricity meter. As far as the lubricant consumed during FSW is concerned, it was calculated by taking into account that 5 l of oil are replace after 30000 h.

FSW outputs are the lubricant inserted as input, which will be directed to disposal, the burr developed during the welding process, which will be set aside for a future recoverable, and the heat emitted into atmosphere during welding. The burr weight was calculated as the weight difference between the two plates measured before and after welding. The heat developed during the FSW process was calculated considering the seam welding mass, using the welding temperature predicted by the finite element method analysis of the process.

3. Results and discussion

3.1. Energy consumption during FSW

Table 1 summarizes the values of the electrical energy consumption during FSW, as a function of different rotational and welding speeds. The total energy absorbed during FSW depends on the welding speed and rotational speed, as shown in Fig. 2. It can be observed that, irrespective of the rotational speed value, an increase in the v value leads to a strong reduction in the energy absorbed during FSW (Fig. 2a), as well as a reduction in production times.

As far as the rotational speed is concerned, a rise in the ω value from 1200 to 1500 rpm involves an increase in the consumption of energy necessary for the faster rotation of the spindle; then, as ω further increases up to 2500 rpm, despite of the tool rotates faster, the energy value tends to decrease (Fig. 2b). Such behaviour can be attributed to the softening of the material that leads to a reduction in the strength as ω increases.

Table 1. Values of total electrical energy absorbed during FSW.

Energy absorbed [MJ]		ω [rpm]			
		1200	1500	2000	2500
v [mm/min]	30	0.82888	0.90804	0.89047	0.88341
	60	0.51478	0.5508	0.53326	0.5200
	100	0.37112	0.40229	0.38593	0.3801

3.2. Life Cycle Impact Assessment of FSW

One of the challenges in conducting a meaningful comparison between different methodologies is the selection of the weighting method. In this work, IMPACT 2002+ method was used in order to link LCI results, via the midpoint categories, to damage categories. The life cycle impact assessment methodology IMPACT 2002+ proposes a feasible implementation of a combined midpoint/damage oriented approach [14]. The IMPACT 2002+ framework links all types of life cycle inventory results via 14 midpoint categories to four damage categories: human health, ecosystem quality, climate change and resources, as shown in Fig. 3.

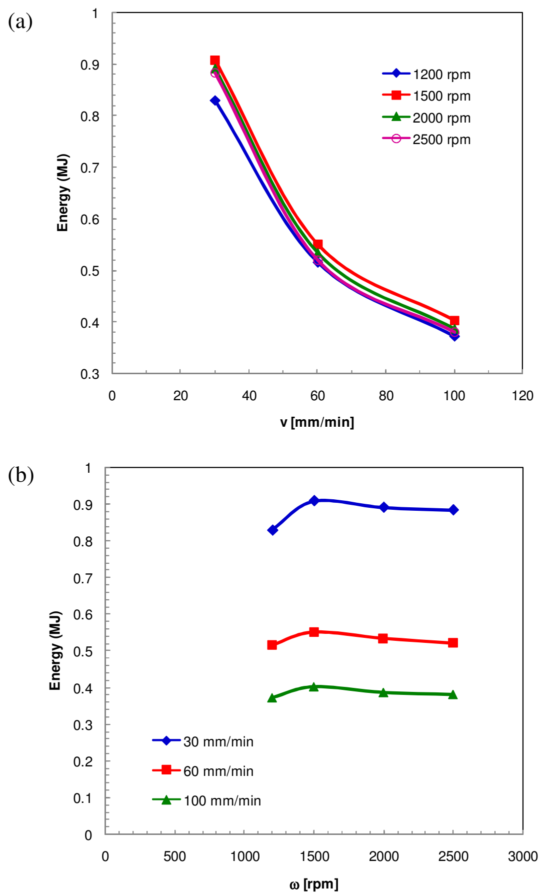


Fig. 2. Effect of process parameters on the electrical energy consumption during FSW.

This takes advantages both from midpoint-based indicators such as CML [15], and damage based methodologies, such as Eco-indicator 99 [16]. All midpoint scores are expressed in units of a reference substance and related to the four damage categories, human health, ecosystem quality, climate change, and resources expressed in DALY, PDF·m2·y, kg CO_2-eq, and MJ, respectively.

Normalization can be performed either at midpoint or at damage level. Table 2 reports the characterization and normalization values of the midpoints corresponding to a typical FSW process. Irrespective of the process parameters taken into account, normalized values highlight that the lubricating oil disposal and the recycling of discarded material, such as burr, have a very low environmental impact. On the contrary, "Respiratory inorganics", "Terrestrial ecotoxicity", "Global Warming" and "Non-renewable energy" are the most important impact categories, from the environmental point of view. In particular, "Non-renewable energy" is the most important impact category in the FSW process. This result is mainly due to the electricity consumption during welding. The normalized values change

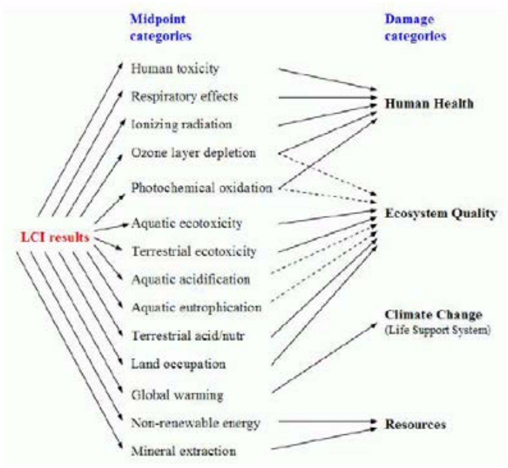


Fig. 3. Overall scheme of the IMPACT 2002+ [14].

Table 2. Midpoints corresponding to a typical FSW process (ω=1200 rpm; v=100 mm/min).

Impact category	Characterization	Normalization
Carcinogens	1.70E-04 Kg C2H3Cl eq	6.76E-08
Non-carcinogens	1.50E-04 Kg C2H3Cl eq	5.83E-08
Respiratory inorganics	3.80E-05 Kg PM2.5 eq	3.75E-06
Ionizing radiation	1.14E-01 Bq C-14 eq	3.38E-08
Ozone layer depletion	5.28E-09 Kg CFC-11 eq	7.81E-10
Respiratory organics	1.14E-05 Kg C2H4 eq	3.43E-09
Aquatic ecotoxicity	2.34E-01 Kg TEG water	8.56E-09
Terrestrial ecotoxicity	6.22E-01 Kg TEG soil	3.59E-07
Terrestrial acid/nutri	8.70E-04 Kg SO2 eq	6.60E-08
Land occupation	7.87E-05 M2org. arable	6.26E-09
Aquatic acidification	2.80E-04 Kg SO2 eq	-
Aquatic eutrophication	6.83E-06 Kg PO4 P-lim	-
Global warming	5.85E-02 KgCO2 eq	5.91E-06
Non-renewable energy	9.44E-01 MJ primary	6.21E-06
Mineral extraction	1.10E-04 MJ surplus	7.08E-10

as a function of the process parameters. Fig. 4 summarizes the values of the most relevant impact categories as FSW is performed at different process parameters.

Results concerning the endpoints or damage categories versus process parameters are shown in Fig. 5. The high impacts, in term of "Resources" and "Climate change", are related to the use of gas, oil and coal necessary for the electricity production. The same reason is responsible for the Human Health impact. As a matter of fact, the fossil fuels combustion produces small inorganic and carcinogenic particles, harmful to human respiratory system. The "Ecosystem quality" impact is mainly related to the soil and water toxicity and, to a lesser extent, to the subsoil exploitation.

Finally, an environmental impact index (EII) was evaluated taking into account all the normalized values of the endpoints, that contribute to the assessment of environmental sustainability of the FSW process (Fig. 6). It can be observed that the FSW process carried out with a rotational and welding speeds of 1200 rpm and 100 mm/min, respectively, is characterized by the lowest environmental impact.

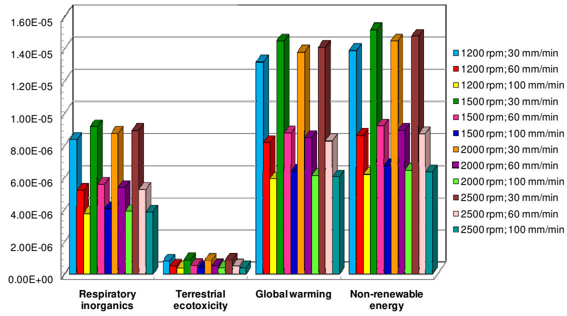
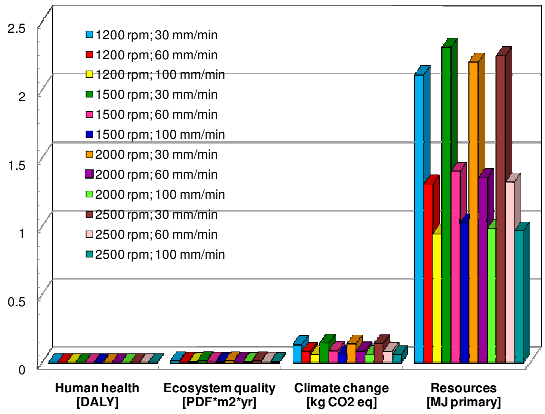
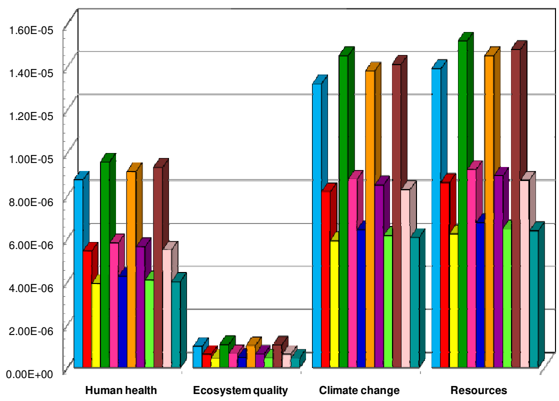


Fig. 4. Effect of FSW process parameters on the main impact categories.



(a)



(b)

Fig. 5. Endpoints of FSW process of AA5754 alloy as a function of process parameters: (a) characterization and (b) normalization.

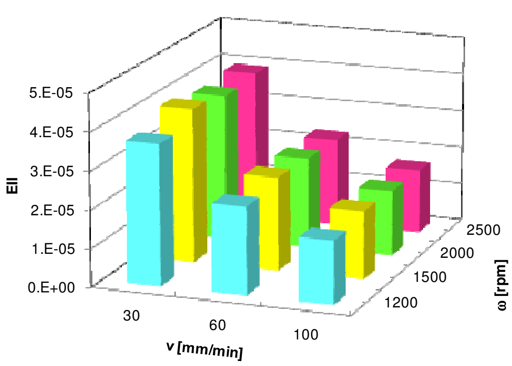


Fig. 6. Environmental impact index of FSW of AA5754 alloy performed under different of rotational and welding speeds.

3.3. Mechanical properties of FSWed joints

The mechanical properties of joints, evaluated in terms of ultimate tensile strength and ultimate elongation, given by samples obtained by FSW performed at different process parameters, are reported in Table 3.

Table 3. Ultimate tensile strength and ultimate elongation of FSWed joints obtained at different rotational and welding speeds (UTS_{BM}=220 MPa; UE_{BM}=34%).

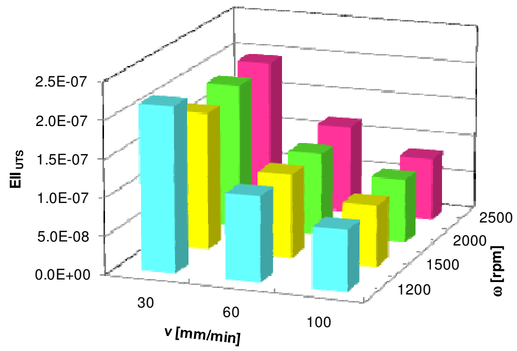
	[rpm] / [mm/min]	1200	1500	2000	2500
UTS [MPa]	30	169.19	223.38	201.67	201.36
	60	203.82	222.00	218.03	197.31
	100	206.33	221.67	202.50	201.25
UE [%]	30	11.60	38.40	19.34	19.00
	60	29.60	32.80	33.80	19.30
	100	33.16	26.70	20.00	19.95

It clearly appears that joints obtained with ω=1500 rpm, irrespective of the welding speed, are characterised by the best combination of UTS and UE values, which are very similar to those provided by the base material (BM). However, under such rotational speed, for each welding speed investigated, the energy absorbed during FSW and, consequently, the environmental impact index, reach the peak values (Fig.s 2 and 6). It might be interesting to establish a relationship among the environmental impact of the FSW process and the mechanical properties of the joints. To this purpose, two further indexes were defined according to the following equations:

$$EII_{UTS} = \frac{EII}{UTS} \quad (1)$$

$$EII_{UE} = \frac{EII}{UE} \quad (2)$$

(a)



(b)

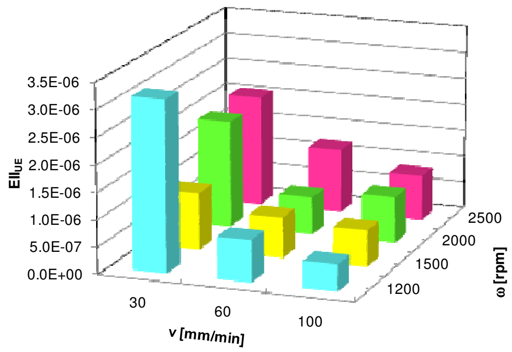


Fig. 7. Effect of the process parameters on the environmental impact index of FSW of AA5754 alloy: (a) for unit ultimate tensile strength, and (b) for unit ultimate elongation.

where EII_{UTS} is the environmental impact index for unit UTS, and EII_{UE} is the environmental impact index for unit UE.

Fig. 7a shows the behaviour of EII_{UTS} versus process parameters; the environmental impact index for unit UTS decreases with increasing v, irrespective of ω, according to the trend exhibited by the EII (Fig. 6). Furthermore, a small effect of the rotational speed on EII_{UTS} appears, consistently with the one shown by the environmental impact index.

The discrepancies with respect to the EII increase as the environmental impact index for unit UE is concerned (Fig. 7b). In particular, the process condition with 1500 rpm and 30 mm/min, characterised by the highest EII (Fig. 6), has a low value of EII_{UE} due to the highest ultimate elongation value exhibited by the joint. Furthermore, in the ranges of welding and rotational speeds varying from 60 to 100 mm/min, and from 1200 to 1500 rpm, respectively, an area characterised by low EII_{UE} values can be observed, indicating that the ductility of joints has a positive effect on the environmental impact index for unit UE.

Finally, the condition with the lowest environmental impact (ω=1200 rpm; v=100 mm/min) is also the most favorable as the EII is related to the mechanical properties of the joints.

4. Conclusions

The life cycle assessment methodology was applied to evaluate the environmental impact of friction stir welding process of AA5754 aluminium alloy sheets, performed under different values of the rotational and welding speeds. To this purpose, FSW experiments were carried out and the relevant data obtained. Results derived using IMPACT 2002+ normalization method has shown that:

- the environmental impact of friction stir welding strongly depends on process parameters;
- the lowest EII value can be obtained at 1200 rpm and 100 mm/min;
- a relationship among the environmental impact of the FSW process and the mechanical properties of the joints has been established; a more pronounced effect of the ultimate elongation on the EII, with respect the ultimate tensile strength, is observed;
- the condition characterised by the lowest environmental impact is also the most favorable as the EII is related to the mechanical properties of the joints.

5. References

[1] European Commission. Energy balance sheets 2009-2010. Eurostat statistial books; 2012.

[2] Gutowski T, Murphy C, Allen D, Bauer D, Bras B, Piwonka T, Sheng P, Sutherland J, Thurston D, Wolff E. Environmentally benign manufacturing: observations from Japan, Europe and the United States. Journal of Cleaner Production 2005;13:1-17.

[3] Duflou JR, Kellens K, Dewulf W. Unit process impact assessment for discrete part manufacturing: a state of the art. CIRP Journal of Manufacturing Science and Technology 2011;4:129-135.

[4] Seuring S. A review of modeling approaches for sustainable supply chain management. Decision Support Systems 2013;54: 1513-1520.

[5] Bevilacqua M, Ciarapica FE, Mazzuto G, Paciarotti C. Environmental analysis of a cotton yarn supply Chain. Journal of Cleaner Production 2014;82:154-165.

[6] Lakshminarayanan AK, Balasubramanian V, Elangovan K. Effect of welding processes on tensile properties of AA6061 aluminum alloy joints. International Journal of Advanced Manufacturing and Technology 2009;40:286–296.

[7] Shrivastava A, Krones M, Pfefferkorn FE. Comparison of energy consumption and environmental impact of friction stir welding and gas metal arc welding for aluminum. CIRP Journal of Manufacturing Science and Technology 2015;9:159-168.

[8] Buffa G, Forcellese A, Fratini L, Simoncini M. Experimental and numerical analysis on FSWed magnesium alloy thin sheets obtained using “pin” and “pinless” tool. Key Engineering Materials 2012;504-506:747-752.

[9] Mishra RS, Ma ZY. Friction stir welding and processing. Materials Science and Engineering R 2005;50:1–78.

[10] Simoncini M, Forcellese A. Effect of the welding parameters and tool configuration on micro- and macro-mechanical properties of similar and dissimilar FSWed joints in AA5754 and AZ31 thin sheets. Materials and Design 2012;41:50-60.

[11] Forcellese A, Simoncini M. Plastic flow behaviour and formability of FSWed joints in AZ31 thin sheets obtained using the “pinless” tool configuration. Materials and Design 2012;36:123-129.

[12] Forcellese A, Gabrielli F, Simoncini M. Mechanical properties and microstructure of joints in AZ31 thin sheets obtained by FSW using “pin” and “pinless” tool configurations. Materials and Design 2012;34:219-229.

[13] Bevilacqua M, Ciarapica FE, Giacchetta G. Design for environment as a tool for the development of a sustainable supply chain. International Journal of Sustainable Engineering 2008;1:188-201.

[14] Jolliet O, Margni M, Charles R, Humbert S, Payet J, Rebitzer G, Rosenbaum R. IMPACT 2002+: a new life cycle impact assessment methodology. International Journal of Life Cycle Assessment 2003;8(6):324-330.

[15] Guinée JB, Gorrée M, Heijungs R, Huppes G, Kleijn R, de Koning A, van Oers L, Wegener Sleeswijk A, Suh S, Udo de Haes HA, de Bruijn H, van Duin R, Huijbregts MAJ, Lindeijer E, Roorda AAH, Weidema BP. Life cycle assessment; An operational guide to the ISO standards; Part 3: Scientific Background. Ministry of Housing, Spatial Planning and Environment (VROM) and Centre of Environmental Science (CML), Den Haag and Leiden, The Netherlands; 2001.

[16] Goedkoop M, Spriensma R. The Eco-indicator 99: A damage oriented method for life cycle impact assessment. PRé Consultants, Amersfoort, The Netherlands; 2000.