Available online at www.sciencedirect.com

ScienceDirect

Procedia Engineering 183 (2017) 206 – 212

Procedia Engineering

www.elsevier.com/locate/procedia

17th International Conference on Sheet Metal, SHEMET17

Analysis of electrical energy demands in Friction Stir Welding of aluminum alloys

Gianluca Buffa[a]*, Davide Campanella[a], Rosa Di Lorenzo[a], Livan Fratini[a] and Giuseppe Ingarao[a]

[a]*Dept. of Industrial and Digital Innovation, University of Palermo, Viale delle Scienze 90128 Palermo Italy*

Abstract

Manufacturing processes, as used for discrete part manufacturing, are responsible for a substantial part of the environmental impact of products. Despite that, most of metalworking processes are still poorly documented in terms of environmental footprint. To be more specific, the scientific research has well covered conventional machining processes, concerning the other processes there is a lack of knowledge in terms of environmental load characterization instead. The present paper aims to contribute to fill this knowledge gap and an energetic analysis of Friction Stir welding (FSW) is presented. Following the CO2PE! methodological approach, power studies and a preliminary time study have been performed in order to comply with the In-Depth approach. The influence of the most relevant process parameters is analyzed regarding the required FSW energy. Finally, a few potential improvement strategies to reduce FSW energy consumption are reported.

Keywords: Friction Stir Welding; Aluminum alloys; Sustainable manufacturing; Energy efficiency

---

1. Introduction

Industry sector plays a relevant role and accounts for almost 40% of the total emissions. Specifically, in the industrial sector CO2 emissions are caused both by direct and indirect emissions. The latter are due to the use of electricity and currently represent 18% of the total amount [1]. Moreover, manufacturing is responsible for about 35% of global electricity use, over 20% of CO_2 emissions as well as over a quarter of primary resource extraction [2].

---

* Corresponding author. Tel.: +39-09123861869; fax: +39-09123861869.
E-mail address: Gianluca.buffa@unipa.it

doi:10.1016/j.proeng.2017.04.022

Looking specifically at metal shaping processes, the sub-sectors Fabricated Metals and Machinery (according to NAICS classification [3]) together account for 4% of the total annual energy consumed by the manufacturing sector in the U.S over the 2010 [4]. Nevertheless, the way to have a complete knowledge about the environmental impact of manufacturing processes is still long. Actually, several processes, particularly non-conventional production processes, are still poorly documented in terms of environmental footprint. In this respect, the CO2PE!-Initiative [5] was launched, this initiative has the objective to coordinate international efforts aiming to document and analyze the overall environmental impact for a wide range of available and emerging manufacturing processes and to provide guidelines to improve these. A methodology for systematic analysis and improvement of manufacturing unit process life cycle inventory (UPLCI) is provided by Kellens et al. [6]. Over the last few years two review papers have been published in the domain of discrete part manufacturing [7, 8]; both of the papers presented the state of the art of sustainable manufacturing processes under different perspectives. Form these papers it is possible to realize that researchers have mainly paid attention to machining processes. Actually, studies addressed at analyzing and modeling the energy efficiency of turning, milling and grinding are already available. All the others discrete metal working processes have been only partially analyzed or even totally neglected.

As far as sheet metal working processes are concerned a few studies have been published though. Some paper focused on forming processes; Cooper et al. [9] presented and environmental analysis of aluminum sheet stamping processes, Santos et al. [10] proposed a comprehensive analysis on the energy efficiency of bending processes while Kellens et al. [11] analyzed the improvements in electrical energy demand by optimizing the press brake architecture. A comprehensive electrical energy demand analysis of Single Point Incremental Forming (SPIF) has been developed by Ingarao et al. [12]. As regards separating processes, some energy and resource efficiency analysis on laser cutting [7, 13] and on punching [14] have been already developed.

In the last decades, researchers have developed new joining technologies to radically settle all the issues linked to the melting-based welding techniques. The solid-state bonding technology allow to obtain sound weld without reaching the melting temperature of the base material. Solid bonding phenomenon occurs in metal materials when a plastic flow is subjected to high pressure and temperature. The third variable that affects the process is the period of time the cited condition are kept. In particular, Friction Stir Welding is a solid-state welding process developed and patented in 1991 by The Welding institute (TWI) of Cambridge. This technology allows the joining of sheet metals thanks to a complex plastic flow of material caused by the action of a properly designed rotary tool that is plunged nearby the edges of the sheets and moved along the welding line. During the process, no filler is used and temperature results to be under the melting point of the base material so that all the issues linked to the melting and solidification of the material are avoided. Different phases can be identified during the process: at the beginning, the tool is plunged at constant velocity in the metal until the bottom of the pin is a few tenths of millimetre far from the bottom of the sheets. The initial inverse extrusion caused by the pin plunging is arrested by the shoulder that consequently generates heat by friction. The material softening caused by the heat flux enable an effective stirring action exerted by both the shoulder and the pin. When the material is heated up enough, the tool is moved along the joining line forming the weld. The process parameters commonly varied during experimental campaigns are the tool rotation and feed rate, which directly affect the heat generation and stirring action, as well as the tool geometry. Joints produced with different combinations of the cited parameters can hence be analysed in order to find out the best configuration.

As a solid-state welding process, it is accepted that the heat input in to the joint is less than the one needed for melting based welding of the same materials. However, to the authors knowledge, only a very limited number of studies can be found in literature focused on the quantitative evaluation of the electrical energy demand of the process. In particular, Shrivastava et al. [15] published the results of a research focused on the development of an analytical model able to predict the energy consumption in FSW of two different aluminium alloys, i.e. AA6061-T6 and AA7075-T6. The obtained results highlighted that power can be estimated based on specific FSW energy, weld area and feed rate. In a second paper by the same authors [16], a comparison is made between energy consumption on FSW and GMAW for variable thickness AA6061-T6 alloy sheets. It was found that FSW consumes 42% less energy as compared to GMAW and utilizes approximately 10% less material for the design criteria of similar maximum tensile force, with a resulting reduction of greenhouse gas emission of 31%. For both the studied the machine used for FSW experiments was a CNC milling machine, which significantly differs in terms of architecture from a dedicated FSW machine, for which force controlled welds can be made through a proper oleodynamic controlled system. Working cycle time study as well as a power study have been performed.

In this paper an Electrical energy demand characterization of AA2024-T4 aluminum alloy in FSW is presented. According to the in-depth approach methodology proposed by Kellens et al., both time study as well as power studies are developed on a FSW dedicated machine tool. Main factors affecting electrical energy demand are highlighted and guidelines for reducing FSW environmental impact are outlined.

2. Experimental set up

. Tests were carried out starting from AA2024-T4 sheets, 3 mm in thickness. Fig. 1 shows a sketch of the process in which the sheet dimensions and the main process parameters are highlighted

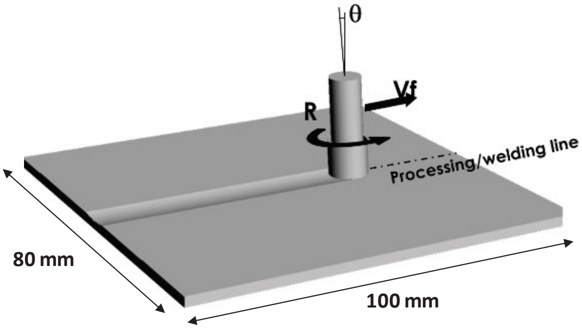

Fig. 1. Sketch of the process and sheet dimensions.

Tool rotation, tool feed rate and tool geometry were selected based on previous preliminary campaign in order to obtain sound joints. The tool, characterized by flat shoulder surface and conical pin, was made of H13 steel heat treated and water quenched in order to reach 52 HRC. Table 1 shows the main technological and geometrical parameters used for this study.

Table 1. Geometrical and technological parameters used for the FSW experiments.

Parameter	value
Tool rotation R [rpm]	1000
Tool feed rate Vf [mm/min]	50, 200
Tilt angle θ	2°
Tool plunge [mm]	0.2
Tool Shoulder [mm]	12
Pin height [mm]	2.6
Pin angle	30°
Pin major diameter [mm]	4.5

Two different machines were used: ESAB LEGIO, a dedicated FSW machine with force controlled vertical axis maximum load of 25 kN and a traditional milling machine. The energy measurements were carried out with a commercial power quality analyzer able to acquire the history of tension, current and power. The methodology applied for quantifying the energy requirements of the respective machine tools tested, and reported in this and following sections, was chosen in compliance with the CO2PE! procedures as specified in Kellens et al. [6]. In particular, the In-Depth approach has been applied to quantify the Electrical energy demand of the analyzed set-up. The time study is performed in order to identify the different use modes of a machine tool and their respective share in the covered times pan. The identified time modes start from the machine tool start-up, over the use phase to finally switching off the machine. Since energy use is determined by the supplied power multiplied by the duration of an operation, the consumed electrical power is then measured for all identified production modes. The power study enables energy shares of different production modes to be quantified and the most consuming phase to be, therefore, identified.

Fig. 2 shows a picture of the cabinet of the dedicated machine during the measurements in which current clamps and tension alligator clips can be seen.

Fig. 2. Cabinet of the utilized machine during the measurements showing current clamps and tension alligator clips.

3. Results

First, the power absorbed by the machine during the process was analyzed and the different phases of the process were highlighted with the aim to identify the contribution of the single process phase. Fig. 3 shows the curve acquired for feed rate equal to 50 mm/min. After the machine switch on, corresponding to the PLC unit start, a first peak of power is registered when the general motors (hydraulic pump, electrical motors, and auxiliary devices) are turned on. Then power sets to about 1300 W, which is mainly due to the pump. During the tool positioning phase the tool is moved both along the welding line and along the vertical direction to match the initial position assigned for the weld. During this phase, two peaks are observed, corresponding to the increased power required by the pump for fast speed and slow speed vertical downward movement in order to move the bottom tip pf the tool pin at a distance of 0.2 mm form the sheets top surface. During the plunge phase, power rapidly increases, reaching the peak value, corresponding to about 4200 W, when the tool shoulder contacts the top surface of the sheets. Then, power gradually decreases because of the sheet softening induced by the heat produced by the friction. During the welding phase, the absorbed power continues to decrease till a steady state value of about 3200 W is reached. In these conditions, an equilibrium is obtained between the heat introduced by the friction forces work and the heat dissipated by conduction and convection. After the completion of the assigned tool path, the tool is lifted out of the sheets, and power rapidly decreases, with a peak corresponding to the hydraulic pump work to vertically move the tool axis. Finally, after stand-by power level is reached again, general motors and machine are sequentially shut down.

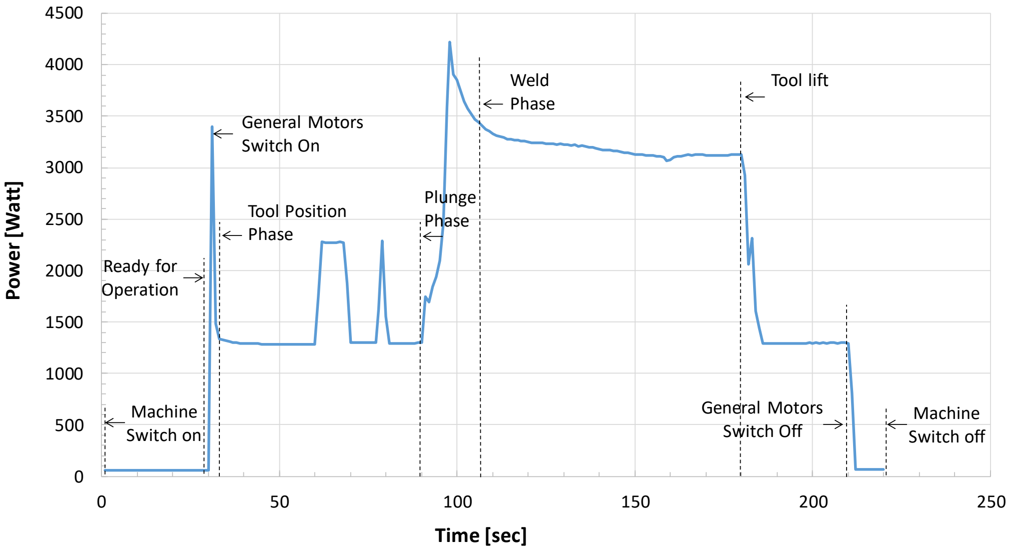

Fig. 3. Power consumption during the process and process phases (R=1000 rpm and v=50 mm/min).

According to the In-depth approach the Time study was developed. In particular, Fig. 4 shows the percentage subdivision of each phase in terms of percentage over the working cycle time, from machine start to machine shut down. The productive phases, i.e. tool plunge, weld and tool lift have been clustered in order to highlight their contribution over the "non-productive" phases.

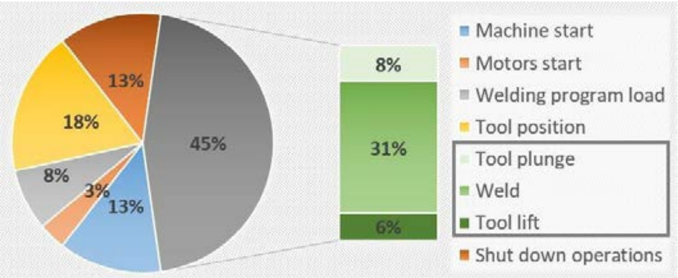

Fig. 4. Time study of the FSW process (R=1000 rpm and v=50 mm/min).

As it can be seen form the figure, only 45% of total time is used for the "productive" phases, being the weld phase 31% of the total, while the rest of the time is used for auxiliary operations and tool position, which is the largest "non-productive" phase. It is worth noting that the length of this operation, defined as the time needed for the tool to come back from the end of the previous weld to the start point of the next weld, is a function of the assigned weld length.

By combining the power and time measurements, the energy required for each phase of the process was identified. The energy shares obtained are shown in Fig. 5. A significant difference is noted with respect to the time study in terms of percentage required by the different process phases. It is noted that the productive phases accounts for the 70% of the total energy. Additionally, 52% of the total is given by the actual weld phase. Again, among the "non-productive" phases, the tool position has a dominant role, being about three times bigger than motor starts, welding program load and shut down operations.

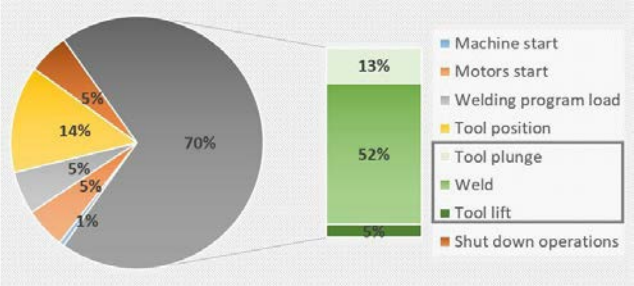

Fig. 5. Energy shares for the FSW process (R=1000 rpm and v=50 mm/min).

In order to investigate the sensitivity of the process against the variation of welding parameters, further tests were carried out with increased feed rate. It is worth noting that, even in these conditions, a defect free joint was obtained with UTS% larger than 75%. Fig. 6 shows the power profile obtained for the weld produced using v=200 mm/min, as compared to the one obtained for v=50 mm/min.

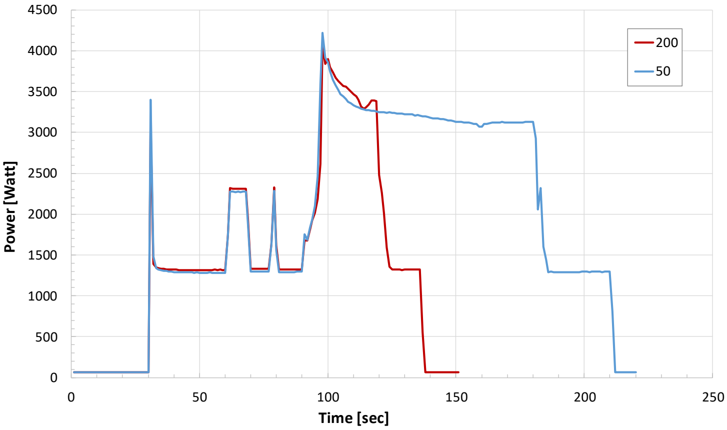

Fig. 6. Power consumption during the process (R=1000 rpm; v=200 mm/min and v=50 mm/min).

A few interesting observations can be made on the power profile. After the end of the plunge phase, a slightly larger power is required for the faster weld. This is due to the colder material encountered by the tool, which is moving with a faster speed; in this way, there is not enough time for the heat to diffuse inside the sheet. Nevertheless, due to the faster speed, the welding time is 25% of the one of the previous weld. In this way, the overall energy consumption ca be significantly reduced. Accordingly, also the energy shares change dramatically (Fig. 7). In this case the productive phases account for only 52% of the total energy while, as expected, the impact of tool plunge, tool lift and “non-productive” phases increases.

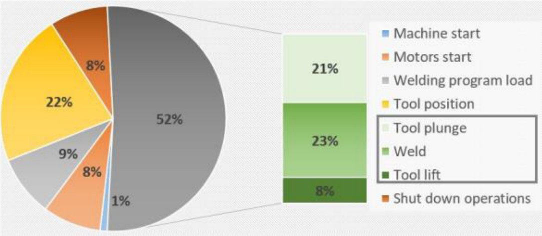

Fig. 7. Energy shares for the FSW process (R=1000 rpm and v=200 mm/min).

4. Conclusions

In the paper a preliminary study on the energy impact of Friction Stir Welding of aluminum alloys is presented. AA2024-T4 aluminium alloy sheets, 3 mm in thickness, were welded under different process parameter. The power required by the machine was measured, during the experiments, through a commercial Power Quality and Energy Analyzer. Production modes of a whole working cycle have been identified as well as their time and energy shares. the main conclusion of the analysis is that the productive time is the dominant factor in the energy demand of FSW processes. For the analysed parameters setting the productive mode energy share varies from 52% to 70% of the total energy. From the acquired power profiles, it arises that maximum power peak is reached when the tool shoulder contacts the sheets top surface. Then, the power decreases during the weld till a steady state is reached. Welding speed has a dramatic influence on both the total energy required and the energy shares. In fact, the power absorbed during the weld only slightly increases due to the increased velocity and consequent colder material, while the time needed for the weld significantly decreases. Hence, a first guideline in order to decrease the energy impact of FSW is to reduce as much as possible, in accordance with the mechanical performance requirements for the joint, the weld phase duration by increasing feed rate.

References

[1] Key Trends and CO2 Emissions Excerpt from: CO2 Emissions from Fossil Fuels, (2015), www.iea.org

[2] Towards a Green Economy, Chapter 7, Manufacturing:in Investing in Energy and Resource Efficiency, United Nations Environment Programme, (2011),

[3] North American Industry Classification System (NAICS), U.S. Census Bureau, (2012), www.census.gov/eos/www/naics

[4] U.S. Department of Energy, (2010), http://energy.gov/eere/amo/ dynamic-manufacturing-energy-sankey-tool-2010-units-trillion-btu

[5] Cooperative Effort on Process Emissions in Manufacturing, (2013)

[6] K. Kellens, W. Dewulf, M. Overcash, M.Z. Hauschild and J.R. Duflou, Methodology for systematic analysis and improvement of manufacturing unit process life-cycle inventory (UPLCI)-CO2PE! initiative (cooperative effort on process emissions in manufacturing). Part 1: Methodology description, International Journal of Life Cycle Assessment. 17 (2012) 69-78.

[7] J.R. Duflou, K. Kellens and W. Dewulf, Unit process impact assessment for discrete part manufacturing: A state of the art, CIRP J. Manuf. Sci. Technol. 4 (2011) 129-135.

[8] K.R. Haapala, F. Zhao, J. Camelio, J.W. Sutherland, S.J. Skerlos, D.A. Dornfeld, I.S. Jawahir, A.F. Clarens and J.L. Rickli, A review of engineering research in sustainable manufacturing, Journal of Manufacturing Science and Engineering, Transactions of the ASME. 135 (2013)

[9] D.R. Cooper, K.E. Rossie and T.G. Gutowski, An environmental and cost analysis of stamping sheet metal parts, Journal of Manufacturing Science and Engineering, Transactions of the ASME. 139 (2017)

[10] J.P. Santos, M. Oliveira, F.G. Almeida, J.P. Pereira and A. Reis, Improving the environmental performance of machine-tools: Influence of technology and throughput on the electrical energy consumption of a press-brake, Journal of Cleaner Production. 19 (2011) 356-364.

[11] K. Kellens, W. Dewulf and J.R. Duflou,Environmental analysis of the air bending process, (2011) 1650-1655

[12] G. Ingarao, H. Vanhove, K. Kellens and J.R. Duflou, A comprehensive analysis of electric energy consumption of single point incremental forming processes, Journal of Cleaner Production. 67 (2014) 173-186.

[13] K. Kellens, G.C. Rodrigues, W. Dewulf and J.R. Duflou,Energy and resource efficiency of laser cutting processes, (2014) 854-864

[14] G. Ingarao, K. Kellens, R. Renaldi, W. Dewulf and J.R. Duflou,Electrical energy analysis and potential environmental improvements of sheet metal punching processes, (2013) 131-136

[15] A. Shrivastava, M. Overcash and F.E. Pfefferkorn, Prediction of unit process life cycle inventory (UPLCI) energy consumption in a friction stir weld, Journal of Manufacturing Processes. 18 (2015) 46-54.

[16] A. Shrivastava, M. Krones and F.E. Pfefferkorn, Comparison of energy consumption and environmental impact of friction stir welding and gas metal arc welding for aluminum, CIRP J. Manuf. Sci. Technol. 9 (2015) 159-168.