Preliminary investigation of the energy consumption in friction stir welding of aluminum alloys

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Abstract. Manufacturing is responsible for significant emissions and energy consumption. However, several manufacturing processes, especially the non-conventional ones, are still poorly investigated from a sustainable perspective. Friction Stir Welding (FSW) is a non-conventional solid-state welding process developed in the last decade which can produce joints with higher mechanical and metallurgical properties. Very few studies exist in the literature on the FSW from a sustainable perspective, so this paper aims to fill this gap of knowledge. Following the in-depth approach of CO2PE! procedure, the power profile of the machine overall the process has been investigated to carry out time and energy studies. The main factors affecting electrical energy demand in the FSW process are highlighted and guidelines for decision-making from an energy-saving perspective are released.

Introduction

Manufacturing has always been seen as the key factor for the prosperity and development of countries [1] [2]. Indeed, manufacturing processes transform materials and information into goods for the satisfaction of human needs. However, transforming raw materials into products is also a significant source of environmental pollution. This environmental pollution can be directly due to manufacturing processes, or indirectly through the energy needed for realizing these processes. Manufacturing waste depends on various factors such as the technology adopted and the material processed. The massive use of energy for industrial operations in Europe is responsible for significant CO2 emissions and thus global climate change. Nevertheless, several manufacturing processes, especially the non-conventional ones, are still poorly investigated from a sustainable perspective [3]. In the last decades, researchers have developed new joining technologies to radically settle all the issues linked to the melting-based welding techniques. Friction Stir Welding (FSW) is a solid-state welding process developed and patented in 1991 by The Welding Institute (TWI) of Cambridge. FSW is a promising solution to produce high-quality welds for low-melting materials, such as aluminum, copper, magnesium, and their alloys, in which the cylindrical tool having shoulder and pin segments rotates and travels along the joint line. Compared to the conventional fusion welding methods, this FSW can produce joints with higher mechanical and metallurgical properties. The main advantage of FSW over traditional fusion welding is the reduction in the heat-affected zone (HAZ), and the joints exhibit excellent mechanical and corrosion resistance properties [4] [5]. The FSW operation does not require any consumables or shielding element techniques in the process, including the electrodes, fillers, and shielding gas. For this reason, it can be thought that the FSW process is more sustainable than conventional ones.

However, the literature lacks guidelines for performing the FSW process by minimizing energy consumption. Also, power consumption during the subphases of the process is not well investigated. This study aims at filling these gaps of knowledge.

In particular, in this paper, an electrical energy demand characterization of the FSW of AA2024-T3 and AA7075-T6 sheets in a lap-joint configuration is presented. According to the in-depth approach methodology proposed by Kellens et al.[6] [7], both time study as well as power studies are developed on a FSW dedicated machine tool. Key factors and subphases in FSW affecting electrical energy demand are highlighted and guidelines for decision- making from a sustainable perspective.

Experimental set-up

Aluminum sheets 158x120 mm, AA2024-T3 and AA7075-T6, were lap-joint welded by FSW. These aluminum alloys are usually difficult to join using traditional welding so FSW can be considered a useful solution. The lap joint configuration is typically adopted in aeronautical industry where structural parts need to be lightweight and mechanically resistant. The final thickness of the lap-joint welded structure is 6.3 mm.

A traditional milling machine Adria Machine PBM-4EVS was used for the experimental activities and thanks to a home-made setup we performed the FSW process. The tool adopted in this study was characterized by a threaded pin having a truncated cone shape. Table 1 contains the main geometrical parameters of the tool.

Table 1. Geometrical parameters of the tool adopted to perform the FSW

Parameter	Value
Pin major diameter (mm)	3.96
Pin minor diameter (mm)	5.40
Shoulder diameter (mm)	13
Tool diameter (mm)	20
Tilt angle (°)	1

The sheets were previously cut in half and then AA 2024-T3 sheets was positioned on the top of the AA 7075-T6 sheets.

Technological parameters to perform the FSW are contained in Table 2. Two levels of tool rotation (1800 rpm and 3200 rpm) have been used for two different welds, by fixing the other process conditions, to analyze the differences in terms of time and energy consumption.

Table 2. Technological parameters of the tool adopted to perform the FSW

Parameter	Value
Tool rotation (rpm)	1800/3200
Tool feed rate (mm/min)	100
Tool plunge (mm)	4.1
Welded length (mm)	90

Qualistar Plus Power and Energy Quality Analyser CA8331 is the device adopted to record power consumption during the FSW process. The machine used to perform the FSW has a three-phase connection without neutral 32 A 380 V. Thus, three tension cables, three crocodile clips and three current sensors MiniFLEX MA193 were used to record the voltage and the current to measure the power. The sampling period for data acquisition was of 1 second [8]. Fig. 1 depicts the setup of the power device connected to the electrical connection of the machine.

Figure 1. Experimental setup to measure current and tension during FSW process

The in-depth approach of the CO2PE! procedure has been adopted in this study. The objective of the CO2PE! Initiative – COOperative effort on Process Emissions in manufacturing – is to cluster forces in different continents in order to analyze existing and emerging discrete part manufacturing processes for their ecological impact in terms of direct and indirect emissions [6]. In this investigation, energy study and time study were carried out based on the measurements to identify focus points for improvements in the FSW process from an energy-saving perspective based on the results generated [9].

Results and Discussion

As above described, an in-depth approach has been carried out in this study to quantify the electrical energy demand of the experimental set-up to perform the FSW to join two aluminum sheets in a lap joint configuration. In particular, the time study was performed to identify the time spent by the machine tool to realize a specific operation by the switching on to the switching off of the machine at the end of the process. Energy study was carried out to highlight the contribution given by each subphase of the FSW process to the overall energy consumption. Fig. 2 shows the power recorded over time during the whole process by selecting a tool feed rate of 100 mm/min and a tool rotation of 1800 rpm.

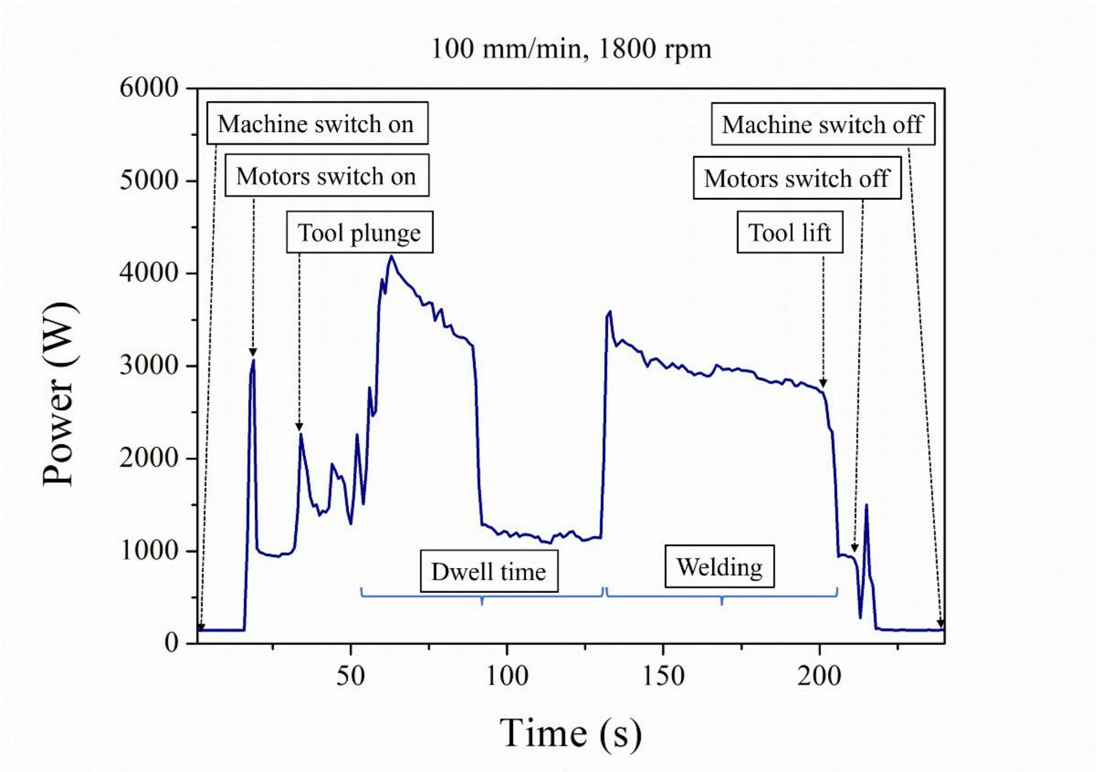

Figure 2. Power consumption profile over time during the FSW process (100 mm/min, 1800 rpm)

The power absorption of the machine during the FSW process has been investigated at different sub-phases to identify each contribution. A power around 150 W is recorded when the machine is switched on. Then, a peak of power of around 3000 W is registered when motors of the machine are turned on. When the tool plunge starts, a peak of power of about 2300 W is reached. When the tool shoulder comes in contact with the top surface of the sheets, power rapidly increases reaching the peak value of 4191 W. This result is very similar to that obtained by Buffa et al. [9]. Then, power gradually decreases because of the sheet softening induced by the heat produced by the friction (dwell time). When the welding starts, a peak value of 3589 W is reached. Then, it rapidly decreases when an equilibrium is obtained between the heat introduced by the friction forces and the heat dissipated by conduction and convection. After the completion of the tool path, the tool is lifted out resulting in a decrease of the power. Consequentially, the motors are switched off before the machine is turned off.

By following the in-depth approach, a time study was developed. Fig. 3 displays a pie chart of the time study: the percentages of the single subphases in terms of time overall process are shown from the machine start to the machine shut down. According to our results, 75% of total time is used for productive phases, including tool plunge, dwell time, welding and tool lift. In the productive phases, 31% is for welding while the remaining 44% is used for tool plunging, dwelling time and tool lifting. Dwell time required the 32% of time. The remaining time is required for non-productive phases including auxiliary operations and tool positioning. It is worthwhile to note that Welding time is function of the length welded. If this length increases, welding time obviously increases.

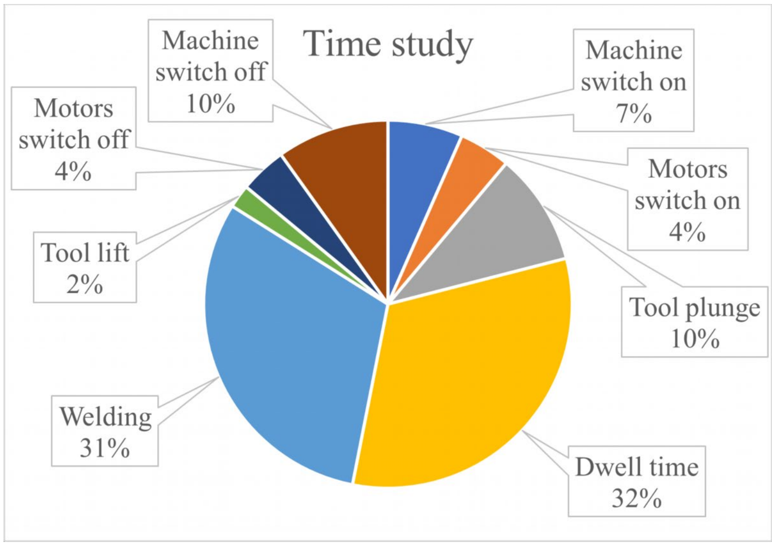

Figure 3. Time study of the FSW process (100 mm/min, 1800 rpm)

By combining power and time measurements, energy consumption has been calculated for each subphase of the whole process. Fig. 4 shows the percentages of the energy study carried out. 94% of the energy consumption is required by the productive phases, including tool plunge, dwell time, welding, and tool lift. Welding time required almost half of the overall energy consumption (45%). Dwell time also required a non-negligible amount of energy consumption due to the fact that power reached over time is higher than other subphases. Thus, in terms of both time and energy consumption, welding subphase plays a dominant role. Instead, terms of power values reached, dwell time plays a crucial role.

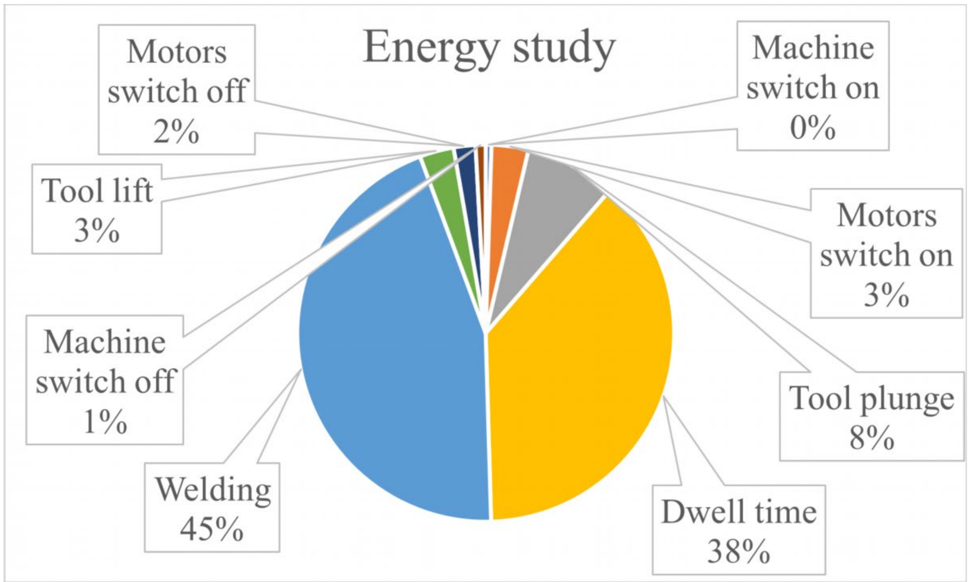

Figure 4. Energy study of the FSW process (100 mm/min, 1800 rpm)

Similarly, Fig. 5 shows the power recorded over time during the whole process by selecting a tool feed rate of 100 mm/min and a tool rotation of 3200 rpm.

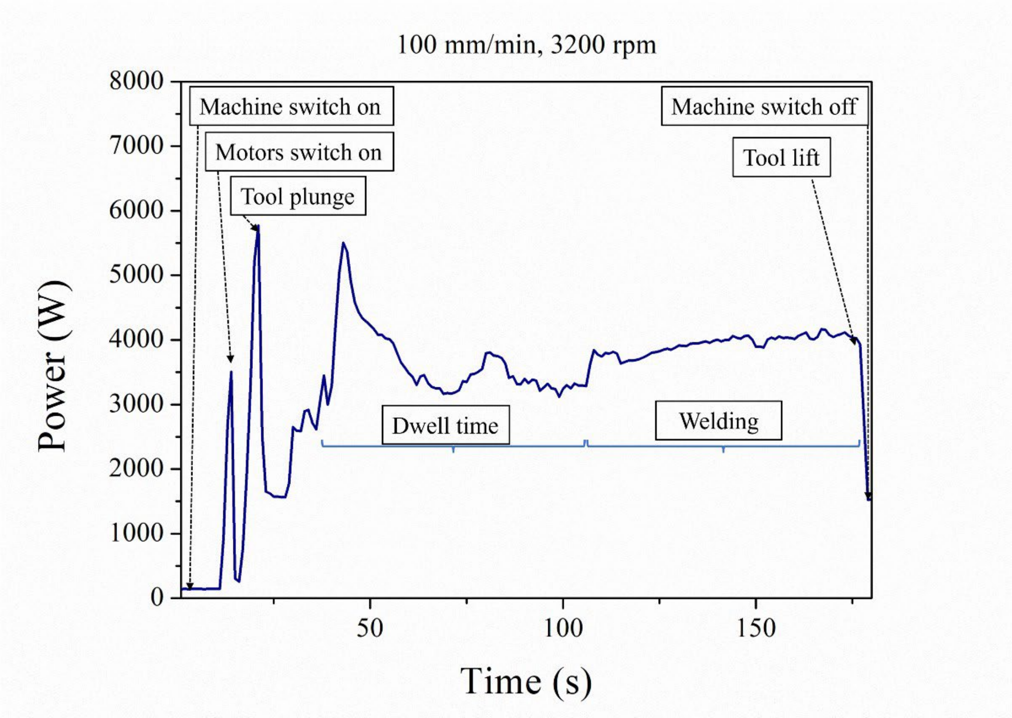

Figure 5. Power consumption profile over time during the FSW process (100 mm/min, 3200 rpm)

Also in this case, power around 150 W is recorded when the machine is switched on. Then, a peak of power of around 3500 W is registered when motors of the machine are turned on. A peak value of 5800 W has been reached when the wool shoulder comes in contact with the top surface of the sheets. Then, power gradually decreases because of the sheet softening induced by the heat produced by the friction (dwell time). When the welding starts, a peak value of 3900 W is reached, very similarly to the power value found by fixing 1800 rpm as tool rotation. Then, it rapidly decreases when an equilibrium is obtained between the heat introduced by the friction forces and the heat dissipated by conduction and convection.

Fig. 6 displays a pie chart of the time study by fixing 100 mm/min and 3200 rpm. According to our results, 79% of the total time is used for productive phases, including tool plunge, dwell time, welding and tool lift. Dwell time required is 34% of the time. The remaining time is required for non-productive phases including auxiliary operations and tool positioning. Very similar percentage results were obtained by observing the time study with 1800 rpm (Fig. 3).

Fig. 7 shows the percentages of the energy study by fixing 100 mm/min and 3200 rpm as process parameters. 79% of the energy consumption is required by the productive phases, including tool plunge, dwell time, welding, and tool lift. Comparing the results obtained in the energy study by using 1800 rpm (Fig. 4), it can be observed a reduction of up to 15% in the energy consumption by increasing the tool rotation by almost up to 50%. Since the duration of all the subphases was very similar among the combinations of process parameters investigated in this study, it can be stated that a lower power was recorded during the productive subphases, especially welding, thus reducing energy consumption. This result can be explained by considering that lower friction forces exist by adopting a higher tool rotation.

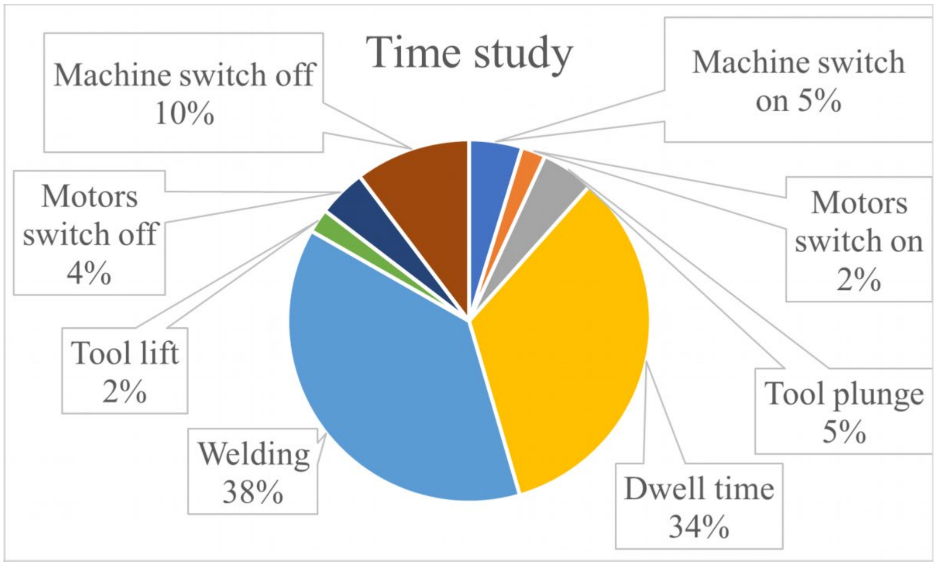

Figure 6. Time study of the FSW process (100 mm/min, 3200 rpm)

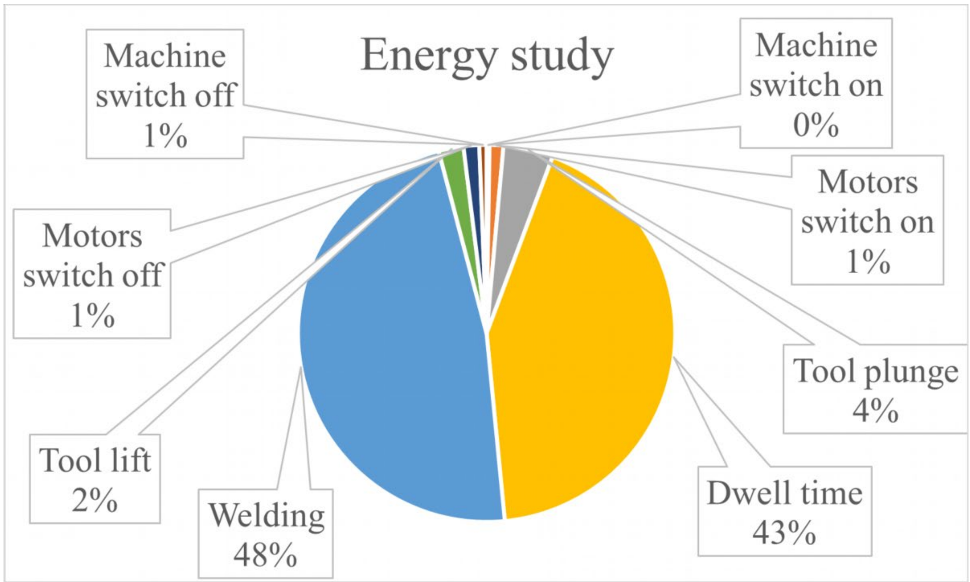

Figure 7. Energy study of the FSW process (100 mm/min, 3200 rpm)

Conclusions

In this paper, a preliminary investigation of the electrical energy demand during the Friction Stir Welding of two aluminum sheets, AA2024-T3 and AA7075-T6 is presented. Current, voltage and power were recorded overall the process from the machine start to the machine shut down during two combination of process conditions. By following the in-depth approach of the CO2PE! Procedure, time study and energy study were carried out to understand the main contribution of each subphase of the FSW process in terms of both time and energy consumption. For the analyzed process conditions power consumption profile over time during the FSW process showed that the highest power peak was reached when the tool shoulder comes in contact with the top surface of the sheets. Productive subphases requires more time and energy than non-productive subphases.

A lower power was recorded during the productive subphases, especially welding, by using a higher tool rotation because of the lower friction forces, thus reducing energy consumption. Welding contribution in terms of time and energy consumption is a consequence of the speed adopted. Thus, according to these preliminary results, the welding phase should be shortened by increasing the feed rate as much as possible to reduce the energy consumption in accordance with the mechanical properties to be obtained for the lap joint. Thus, further investigation of this study may regard the variation of the process conditions to understand their effect on the mechanical properties from an energy-saving perspective. Also, an LCA should be carried out to investigate whether and eventually how each single process condition influences the emissions on the environment for a better decision-making.

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