G Model
CIRPJ-290; No. of Pages 10
ARTICLE IN PRESS

CIRP Journal of Manufacturing Science and Technology xxx (2015) xxx–xxx

Contents lists available at ScienceDirect

CIRP Journal of Manufacturing Science and Technology

journal homepage: www.elsevier.com/locate/cirpj

Comparison of energy consumption and environmental impact of friction stir welding and gas metal arc welding for aluminum

Amber Shrivastava [a], Manuela Krones [b], Frank E. Pfefferkorn [a,*]

[a] Department of Mechanical Engineering, University of Wisconsin-Madison, Madison, WI, USA
[b] Professorship of Factory Planning and Factory Management, Technische Universität Chemnitz, Chemnitz, Germany

ARTICLE INFO

Article history:
Available online xxx

Keywords:
Energy consumption
Environmental impact
Life cycle assessment
Friction stir welding
Gas metal arc welding

ABSTRACT

One of the advantages of friction stir welding (FSW) is reduced energy consumption as compared to arc welding processes. This advantage has been predicted and qualitatively established. However, a quantitative analysis based on energy measurements during the processes and how to equitably compare them is missing. The objective of this work is to quantitatively compare the energy consumption associated with the creation of full-penetration welds in aluminum 6061-T6 workpieces by FSW and gas metal arc welding (GMAW) processes. The workpiece thicknesses for the two processes (5-mm-thick for FSW and 7.1-mm-thick for GMAW) are chosen such that the maximum tensile force sustained by the joints during tensile testing is similar. This accounts for material saving due to the higher ultimate tensile strength resulting from FSW. The energy consumed for any pre-processes, the welding processes, and post-processes was measured. Finally, a life cycle assessment (LCA) approach was used to determine and compare the environmental impact of FSW and GMAW. For the welding parameters used in this study joining by FSW consumes 42% less energy as compared to GMAW and utilizes approximately 10% less material for the design criteria of similar maximum tensile force. This leads to approximately 31% less greenhouse gas emissions for FSW as compared to GMAW. Both, the lower energy consumption during FSW, and involved pre and post processes contributed in the overall energy reduction.

Introduction

Friction stir welding

Friction stir welding (FSW) was invented by Wayne Thomas at *The Welding Institute (TWI)* in 1991 [1]. FSW is a metal joining process in which two or more components are plastically deformed and mechanically intermixed under mechanical pressure at elevated temperatures [2,3]. These joints are created below the solidus temperature of the workpiece material, which makes FSW a solid-state welding process. Fig. 1 shows a schematic of the FSW process for a butt weld. The process involves a non-consumable rotating FSW tool, with specifically designed probe (pin) and shoulder. The FSW tool is plunged with a downward force into the workpiece. Once the probe is completely inserted in the workpiece and the shoulder makes contact with its surface, the tool is traversed along the weld seam (butt welding) or defined path (lap welding, bead-on-plate, friction stir processing). The tool is retracted at the end of the weld. Initially, heat is generated due to friction between the tool and workpiece, which facilitates plastic deformation of the parent material (*i.e.*, stirring). Once, the material is being plastically deformed in the stir zone, heat is generated by friction and heat dissipation due to plastic deformation. The plasticized material is mixed and extruded past the tool and finally, it is forged together in the wake of the tool. FSW as a metal joining process is gaining acceptance in industrial application as the joint qualities and the cost benefits are better understood. Most friction stir welds are currently made in aluminum and magnesium alloys; however, the application of FSW to dissimilar materials and higher melting temperature alloys (*e.g.*, ferrous alloys) is increasing.

Gas metal arc welding (GMAW)

Gas metal arc welding (GMAW) was developed in the 1950s. It was formerly known as metal inert gas (MIG) welding [4]. It is a fusion welding process in which the workpieces melt and re-solidify to make the joint. In GMAW, the heat required for melting

* Corresponding author. Tel.: +1 608 263 2668.
E-mail address: pfefferk@engr.wisc.edu (F.E. Pfefferkorn).

http://dx.doi.org/10.1016/j.cirpj.2014.10.001
1755-5817/

Please cite this article in press as: Shrivastava, A., et al., 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), http://dx.doi.org/10.1016/j.cirpj.2014.10.001

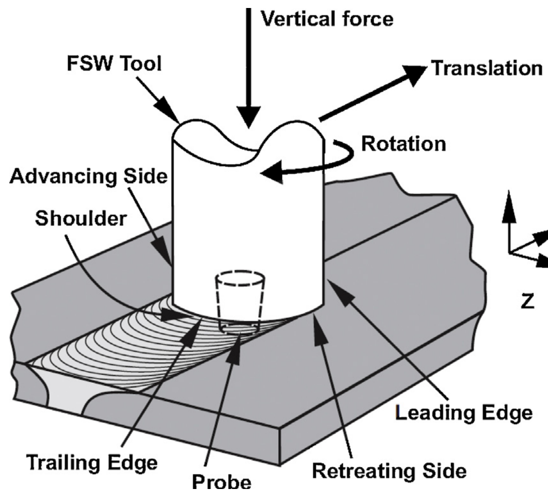

Fig. 1. Schematic of friction stir [butt] welding (FSW).

the workpieces is obtained from electrical energy. During welding, a consumable wire electrode is utilized which establishes the arc and melts in the process to feed additional material to the melt pool. The consumable wire electrode is continuously fed through a nozzle. The weld-area/melt-pool is shielded by an effectively inert atmosphere of argon, helium, carbon dioxide or various other gas mixtures. Fig. 2 shows a schematic of the GMAW process. GMAW is extensively used in the metal fabrication industry [4] and is suitable for welding both ferrous and non-ferrous metals.

Energy consumption and process emissions

It is believed in the welding community (research and industry) that less energy is consumed during FSW as compared to any fusion welding method. This is due to lower welding temperatures achieved during FSW and the solid-state nature of the process, *i.e.*, no melting of the workpiece material. Lakshminarayanan et al. [5] estimated the heat inputs for GMAW and gas tungsten arc welding (GTAW) and compared them to the heat input for FSW. 6 mm thick aluminum 6061 plates were butt welded by these processes. The heat input was estimated only for the processes, and pre and post-processes were not accounted in these calculations. The heat input for FSW was estimated according to Heurtier et al. [6]. The heat inputs for GMAW and GTAW were found to be 2 times and 1.5 times the heat input for FSW, respectively. Lakshminarayanan et al. [5] also found that the tensile strength of the FSW joints was 34% and 15% greater than the GMAW and GTAW joints, respectively.

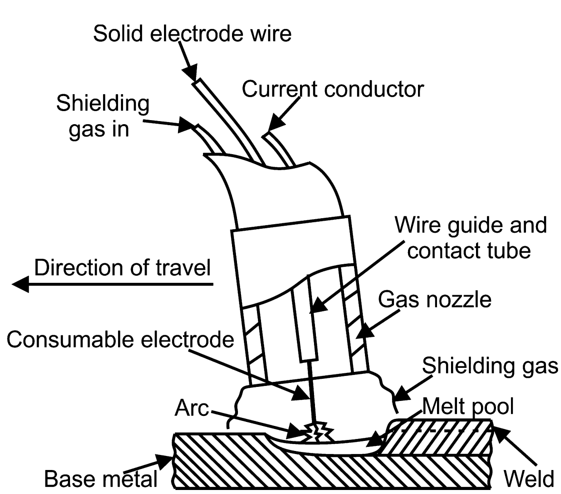

Fig. 2. Schematic of gas metal arc welding (GMAW) process [4].

Prasad and Prasanna [7] studied the hardness and microstructure in the welded material for FSW and GMAW joints. It was revealed that the heat affected zone (HAZ) in FSW welds was narrower than in their GMAW welds: a result of the different heat input.

There are aspects of FSW that in addition to lower welding temperatures could result in lower resource utilization, energy consumption, emissions, health hazards and environmental effects as compared with fusion welding processes (*e.g.*, GMAW, GTAW, SMAW, *etc*). Balasubramanian [8] stated that more than 10,000,000 workers worldwide are employed full time as welders and a higher number of workers perform welding intermittently as part of their job. The common health disorders in full time workers due to the welding emissions include: irritation of the eyes, nose and throat, pulmonary edema, and Parkinson's disease. Health hazards due to welding processes are mainly caused by particulate emissions in the breathing zone of the welder. Depending on the size of the particulates, their influence on the welder's body may change. Therefore, particulates are described in categories according to their maximal size in μm. Pfefferkorn et al. [10] found that FSW leads to average emissions of PM 2.5 particulates of 0.018–0.029 mg/m^3 for Al 6061-T6 and 0.015–0.022 mg/m^3 for Al 5083-H111. Cole et al. [11] analyzed the rate of PM 5 particulates for GMAW of Al 6061 in the welder's breathing zone and found an average of 12 mg/m^3 for welding with Al 4043 wire and 14.1 mg/m^3 for Al 5356 wire. Matczak and Gromiec [12] analyzed PM 0.8 particulate emissions while welding Al 5083 in industrial welding shops. Based on their results, the average emissions over an average 8-h-shift are 1 mg/m^3 with a maximum of 3.6 mg/m^3. These results suggest that particulate emissions from FSW of aluminum are orders of magnitude smaller than GMAW, which will result in significantly lower air handling and filtration requirements.

Dawood et al. [9] measured the mechanical properties and gaseous emissions from FSW and GMAW of 3-mm-thick 1030 aluminum. The carbon monoxide and carbon dioxide emissions for GMAW were approximately 3.7 and 1.6 times greater than, respectively, the corresponding emissions during FSW. It was concluded that FSW is relatively green, environmentally-friendly and results in superior welding properties compared to GMAW, when welding the same thickness aluminum material.

FSW of aluminum alloys does not require shielding gases or flux, and does not use filler material. There are no pre-processing operations required for FSW. Chamfering/edge-preparation of workpieces is not required for FSW, even for 50-mm-thick welds. Cleaning of edges is not required to create the joint. Friction stir welding has few, or no, post-processing requirements because of the lower temperatures experienced and lack of filler material. The only common post-process is associated with eliminating the exit hole created when the FSW tool is retracted. The lower weld zone temperatures result in little or no thermal distortion of the structure, therefore, little or no straightening is required. The lack of filler material results in a smooth weld surface that does not require grinding or machining. The fine microstructure produced in a friction stir weld and the lower amount of annealing/aging that occurs during the process results in mechanical properties that are often better than comparable fusion welds. This can reduce the need for post-welding heat treatment. The energy consumption associated with the common pre-processing, welding process, and post-processing steps of FSW and GMAW is qualitatively shown in Fig. 3.

In industry, FSW is predominantly used for welding aluminum and magnesium alloys. The metallurgical developments