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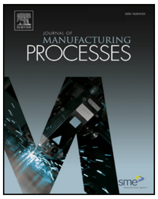

Welding parameter maps to help select power and energy consumption of friction stir welding

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ABSTRACT

The objectives of this work are to investigate power and energy consumption of friction stir welding over a wide range of welding parameters and to provide a welding parameter map synthesized with their relations to welding quality. Friction stir welding has been known as an energy efficient welding technology because the whole process takes place in the solid-state, *i.e.*, no excessive heat is needed to melt the workpiece. However, the study of the energy consumption and resulting welding quality across a wide parameter window has not been established inclusively. In this work, a series of 6061-T6 aluminum butt welds were created by friction stir welding across various welding parameters (spindle speeds and weld speeds). In order to understand the overall power and energy consumption, both mechanical process power and electrical wall plug power were measured on the 3-axis CNC mill used to perform the welds. Additionally, temperatures near the workpiece surface and weld roots were measured. The resulting weld quality was assessed by conducting tensile tests of weld cross-sections to determine the location of failures. The results of the power/energy, temperatures, and tensile tests were incorporated, producing an inclusive welding parameter map. The welding parameter map helps identify minimum power and minimum energy consumption points within the process constraints needed for maintaining good welding quality. The general approach presented in this paper can be applied to different welding setups and conditions.

1. Introduction

Manufacturing consumes substantial amounts of energy and accounts for more than 34% of the total energy use in the United States [1]. Both increasing electricity costs and the awareness of environmental impacts have prompted efforts to implement “green manufacturing” strategies that focus on energy efficiency and minimizing waste and emissions [2].

One technique that falls into this category is friction stir welding, a relatively new joining process invented at The Welding Institute in 1991 [3]. Friction stir welding is a solid-state joining process which enables two or more materials to be plastically deformed and physically intermixed [4,5]. A schematic of the friction stir welding process is shown in Fig. 1. During friction stir welding, a non-consumable rotating tool, consisting of a shoulder and a probe, plunges into the workpiece such that the shoulder and the probe are in contact with the workpiece surface. The process creates a large amount of plastic deformation under the rotating tool due to an elevated temperature field resulting from the combination of high tool-workpiece interface forces and friction. The tool moves along the joint interface, joining the adjacent workpieces as the tool leaves the processing zone [6].

The entire process takes place in the solid-state, where workpiece temperature remains below the solidus temperature. Due to the absence of melting, friction stir welding is an energy efficient process relative to arc welding, where joining materials are melted. The lower temperature of the process enables joining with lower distortion and lower residual stresses. In addition, the weld does not experience problems related to re-solidification, such as reinforcement dissolution, porosity, embrittlement, and cracking. Friction stir welding has also been shown to emit significantly less airborne particles than conventional arc welding [7]. For these reasons, friction stir welding has become an attractive joining process for many industrial applications, including consumer electronics, aerospace, automobile and maritime [8–15].

2. Motivation

Energy consumption of friction stir welding and gas metal arc welding of 6061-T6 aluminum has previously been compared [16]

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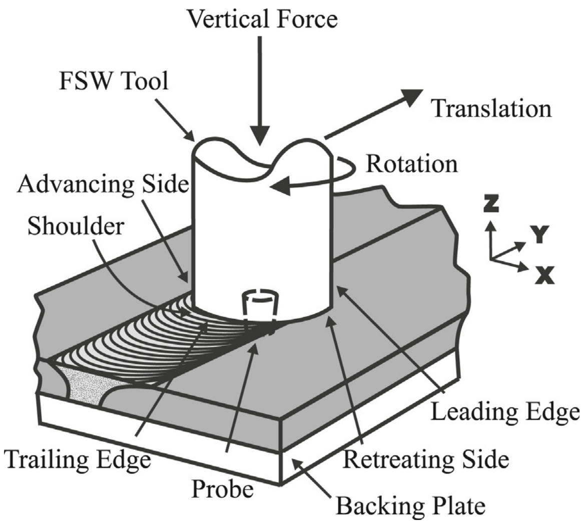

Fig. 1. A schematic of the friction stir welding process.

using a single parameter condition (weld speed: 400 mm/min, spindle speed: 1100 rpm and steel backing plate) where it was found that overall energy consumption in friction stir welding was 40% less as compared to gas arc welding for this particular weld scenario. However, other than the work in [16], we are unaware of research that has investigated the energy consumption of friction stir welding across a wider parameter window and its relation to welding quality. The link between energy consumption and weld quality is affected by various welding conditions, such as spindle speed, weld speed [17,18], plunge force [19] and backing plate thermal diffusivity [20]. The present work bridges these areas (efficiency and quality) by investigating how friction stir welding parameters, that are known to influence strength, affect the overall process energy consumption.

In the present work, we experimentally investigate the energy consumption and resulting weld quality in friction stir butt welds of aluminum 6061-T6 plate over a range of welding conditions (spindle speed and weld speed). To evaluate energy consumption, both electrical input power [wall plug] and mechanical output power [process] of the friction stir welding machine were monitored. Additionally, the temperature was monitored in the weld zone near the workpiece surface and near the root using thermocouples embedded in the friction stir welding tool shoulder and probe respectively. Weld quality was measured by performing tensile testing of weld cross-sections. The results of the energy, temperature, and quality tests are presented and synthesized.

3. Approach

The rate of energy flow (power) during friction stir welding can be divided into two steps. The first step involves the conversion of electrical power, supplied to the machine from an external power source and referred to here as wall power ($P_{wall\ plug}$), into the mechanical power of the machine ($P_{process}$) and electrical and mechanical losses (P_{loss}). The second step involves the conversion of mechanical power of the machine tool ($P_{process}$) to thermal heat flow inside the workpiece, backing plate and ambient atmosphere and the plastic deformation/transport of welded material (P_{out}). The overall energy flow during friction stir welding is presented in Fig. 2. In this work, we are interested in investigating the power and energy consumption of friction stir welding. As such, the power flow variables of interest include the process power, ($P_{process}$), which measures the required input mechanical power as a function of weld parameters, independent of machine efficiency, and external power ($P_{wall\ plug}$) which refers to the required machine electrical power and thus is a direct measurement of energy consumption, albeit a function of the machine's efficiency.

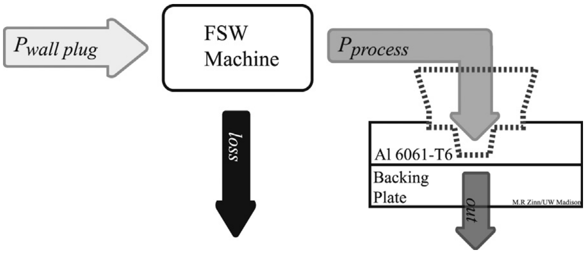

Fig. 2. Schematic of simplified power flow in the friction stir welding process.

For the friction stir welding process under consideration, the process power, $P_{process}$, consists of the mechanical power delivered through the rotation of the spindle and through the linear motion of the tool along the weld. In this case, we evaluate the average process power over the entire weld length, given as:

$$P_{process} = \underbrace{\tau_{avg}\cdot\omega\cdot\frac{2\pi}{60}}_{\text{spindle rotation power}} + \underbrace{f_{travel\,avg}\cdot v\cdot\frac{1}{60\cdot 1000}}_{\text{linear motion power}} \quad \left[W=\frac{J}{s}\right] \tag{1}$$

where τ_{avg} and $f_{travel\,avg}$ are the average spindle torque, expressed in units of Newton-meters, and average traverse force, expressed in Newtons, respectively. The spindle speed, ω, and traverse speed, v, are expressed in units of revolutions per minute and mm/min, respectively.

4. Experimental procedure

In our experimental study, 4.76-mm-thick aluminum 6061-T6 plates were friction stir welded over a range of welding parameters. It has been reported that primary process parameters that affect the heat input to the process include spindle speed and weld speed [21]. To inclusively investigate the effect of welding parameters on energy consumption and resulting mechanical properties, the full process window, as defined in Fig. 3, as a function of spindle and weld speed, was investigated. The process is constrained by several factors including spindle power limitations and weld material temperature constraints. A complete discussion of the process constraints is given in Section 5.4.

All welds in this study were butt welds performed on a commercial computer numerically controlled (CNC) milling machine (HASS TM-1) using a friction stir welding tool fabricated from H13 tool steel. The tool features include a concave shoulder (diameter of 15 mm) and a threaded, conical probe (diameter tapers from 7 mm to 5 mm) with three flats [22]. Two thermocouples were embedded in the tool, one

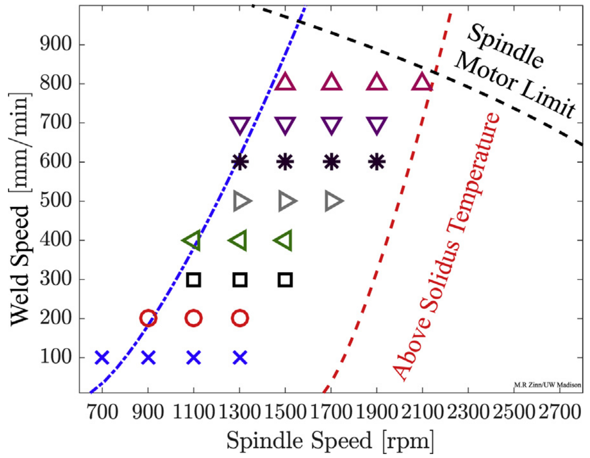

Fig. 3. Test matrix for parameter variations used in this study when making 4.76-mm-deep full-penetration friction stir welds in aluminum 6061-T6.