Measurement 88 (2016) 331–342

Contents lists available at ScienceDirect

Measurement

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

Calibration of dynamic tool–workpiece interface temperature measurement during friction stir welding

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ARTICLE INFO

Article history:
Received 29 June 2015
Received in revised form 24 February 2016
Accepted 29 February 2016
Available online 19 March 2016

Keywords:
Thermocouple
Calibration
Transient response
Friction stir welding

ABSTRACT

The objective of this work is to accurately measure the transient temperatures at the tool–workpiece interface during friction stir welding (FSW) using thermocouples that are embedded in the tool. Temperature sensors embedded in the friction stir (FS) tool provide a non-consumable localized temperature measurement capability that is crucial for process research, development, and control. A modification of the ASTM E-1461 standard for measuring thermal diffusivity with pulses of heat flux is proposed for calibrating the transient response of temperature sensors located near the surface of the FS tool. These tests enable the calculation of each sensor's time constant, which are used in one-dimensional analytical models of the dynamic response to calculate the true interface temperature. Time constants between 21 and 43 ms are measured for 0.25-mm-diameter, sheathed thermocouples located at the FS tool surface.

1. Introduction

Friction stir welding (FSW) is a relatively new welding process developed in 1991 at The Welding Institute (TWI) in the United Kingdom [1]. The main feature of the process is that the material does not melt during welding, *i.e.*, temperatures stay below the solidus. Creating a metallurgical joint in this temperature range results in desirable properties. Furthermore, the process can be more energy efficient and environmentally friendly than contemporary fusion welding processes [2], and has the potential for broad application [3].

The basic FSW apparatus consists of a non-consumable rotating friction stir (FS) tool, the workpieces, a fixture capable of rigidly holding the workpieces, and a machine for generating the relative motion between the FS tool and workpieces as well as the required spindle torque, plunge and traverse forces (Fig. 1). The FS tool consists of a nominally flat shoulder with a protruding probe, which is usually frustum shaped and includes features such as flats and threads. During the weld, the rotating tool is moved into the workpiece to a desired plunge depth. After the FS tool reaches its plunge depth the traverse portion of the weld begins. During this phase, the tool continues to rotate as it travels along the weld seam. The rotation of the FS tool moves and mixes the workpiece material resulting in a solid-state joint being formed behind the tool. The weld zone material experiences severe plastic deformation (high strains and strain rates), hence the process causes significant microstructural evolution for typical weld parameters [3,4].

1.1. Importance of temperature in friction stir welding

As is common to other types of welding, knowledge of the heat input and characterization of the weld zone temperature distribution provide important insights into

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http://dx.doi.org/10.1016/j.measurement.2016.02.065

Nomenclature

c	specific heat, J/kg K	T_{ini}	initial material temperature, K
C_0	temperature fit coefficient of magnitude, –	T_{max}	maximum temperature rise, K
d_p	FS tool probe diameter, m	x	distance from surface of material; distance from tool shoulder, m
d_s	FS tool shoulder diameter, m		
E''	amount of instantaneous energy released per unit area, J/m^2		
k	thermal conductivity, W/m K	*Greek symbols*	
L	distance to temperature measurement location, m	α	thermal diffusivity, m^2/s
		ΔT	temperature oscillation amplitude, K
P	power, W	ρ	density, kg/m^3
t	time, s	σ_τ	standard deviation of measured time constant
T_0	initial thermocouple temperature, K	τ	time constant governing dynamic response, s
T	temperature, K	ω	angular frequency of spindle, rad/s

the process. Fig. 2 shows the friction stir weld zone in greater detail.

It is the stir zone temperature distribution along with the deformation history that determines the microstructural changes that the material undergoes. The microstructure is related to the weld strength, ductility, and toughness. Therefore, the mechanical weld properties are related to the temperatures in the weld-zone. For example, Peel et al. [5] report that resultant weld properties were dominated by the thermal input to the weld. They even go so far as to state that thermal effects are more important than the mechanical deformation caused by the FS tool. Gratecap et al. [6] found a qualitative effect of weld temperature on weld quality. Edwards and Ramulu [7] demonstrate that weld zone microstructure (grain size) is qualitatively related to the weld-zone temperature. Recently completed measurement of weld-zone temperature by Fehrenbacher et al. [8] showed that weld failure mode and weld efficiency can be related to a minimum temperature limit. Fast and accurate measurement of weld zone temperature is of great interest for process understanding and control in friction stir welding.

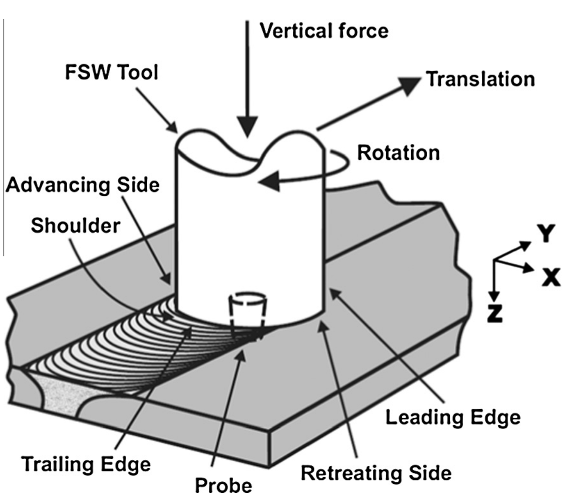

Fig. 1. Schematic of friction stir butt weld [3].

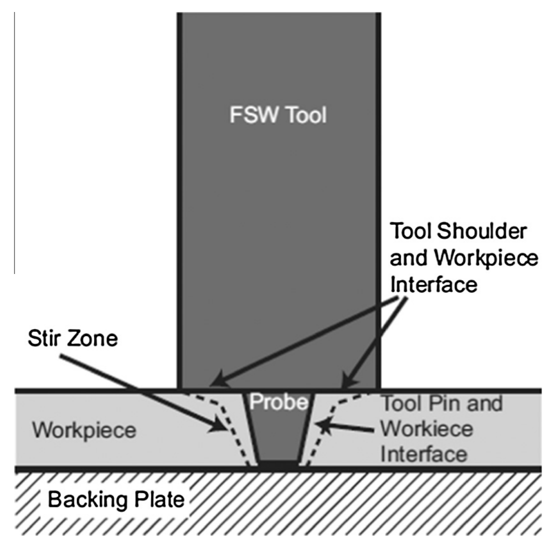

Fig. 2. Areas of interest related to temperature in friction stir welding (FSW).

Fehrenbacher et al. [9] used the same thermocouple-based temperature sensors described in this paper to measure the FS tool–workpiece interface temperature and maintain a desired temperature in the presence of disturbances. Shrivastava et al. [10] describe how changes in measured temperature can be related to the creation of a discontinuity (*e.g.*, void) in the weld, which require the accurate detection of faster temperature transients as the void size decreases and frequency of discontinuity occurrence increases.

1.2. Temperature measurement in friction stir welding

As is also common to other welding processes, measurement of the weld zone temperature provides an instrumentation challenge. An ideal temperature measurement system would provide information with fine spatial and temporal resolution throughout the weld zone. In