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Research Paper

Thermal optimization of friction stir welding with simultaneous cooling using inverse approach

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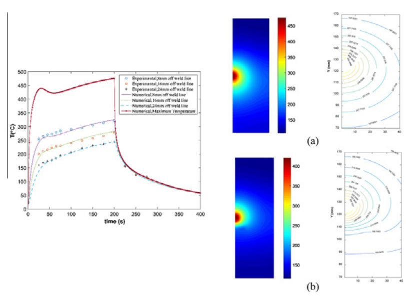
HIGHLIGHTS

- Obtaining heat input of process using temperature measurements off weld line.
- Determination of Johnson-Cook's effective coefficient.
- Obtaining maximum temperature for joining process using inverse method.
- Thermal optimization recommends appropriate welding and cooling parameters.

GRAPHICAL ABSTRACT



Estimated maximum temperature within welding stage; experimental and numerical

Temperature distribution of experiment without cooling (a) and with simultaneous cooling (b) at t=200s

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ABSTRACT

Study utilized an inverse heat transfer approach in order to obtain heat input during friction stir welding with simultaneous cooling process. It specifically applied the conjugate gradient method using limited experimental temperatures in space and time. Experimental dataset was either inputs for convergence of inverse algorithm or outputs for verification of final predicted results. The three-dimensional finite element model was used for direct problem. To obtain better precision and simulate real practical process, slip function has been defined by exponential approximation of matrix rotary speed and calculated Johnson-Cook coefficient as an immeasurable term of analytical solution, which is the main output of inverse determination. Weld line maximum temperature was calculated as second immeasurable parameter. Optimization of normal force and cooling performance for friction stir welding of Al5052 aluminum alloy sheet was sought. Numerical results were consistent with experimental recorded temperatures and the optimization results were acceptably close to the desired maximum temperature, which is practically achievable.

1. Introduction

Friction stir welding (FSW) is solid-state joining process, which can be used for either similar or dissimilar two facing parts of metals without contribution of melting. Physical engagement of tool and workpiece is deducted to attainment of a region, which is affected by torque, compression, and generated heat. This region is called thermo mechanical-affected zone (TMAZ) [1]. Concomitant plastic deformation and friction provide heat input of welding, which induces TMAZ to be softened and mixed. After occurring temperature apex, which is normally lower than solidus temperature of workpiece, throughout welding stage, temperature of workpiece decreases and plasticized material begin to form continuous solid joint within cooling stage, which could be controlled over time by corresponding parameters [2].

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Nomenclature

$B_{x,y}$	Nozzle outlet dimensions (m)
c	heat capacity (J/g °C)
d	direction of descent
F	normal force (kN)
h	heat convection coefficient (W/m^2 °C)
H	heaviside function
I	number of measurements in time
k	thermal conductivity (W/m °C)
M	number of thermocouples
N	number of inputs to inverse algorithm
P	exerted normal pressure (kN/m^2)
q	heat flux on boundary (W/m^2)
r	radial distance (m)
r_0	shoulder radius (m)
R	measured temperatures matrix
s	power coefficient of Johnson-Cook correlation for temperature
S	objective function
t	time (s)
t_v	slip instant (s)
T_{im}	calculated temperature matrix
T_{ref}	reference temperature (°C)
T_{melt}	melting temperature (°C)
U	transverse speed of tool (mm/s)
X, Y, Z	fixed coordinate system components
X', Y', Z'	moving coordinate system components

Greek Symbols

α	thermal expansion coefficient (μm/m °C)
β	search step size
γ	conjugation coefficient
δ	slip function
δ_0	empirical constant of slip growth
η	mechanical efficiency
θ	angle of interface elements respect to weld line (Rad)
κ	modification coefficient
λ_v	Exponential approximation coefficient of slip function
μ	friction coefficient
ξ	effective Johnson-Cook coefficient (MPa)
ρ	density (kg/m^3)
ϕ	unknown parameter
σ	average measurement error
ω	rotary speed of tool (rev/min)
ω_0	reference rotary speed of tool (rev/min)
τ	shear stress (MPa)

Subscripts

Ad	adjusted
ex	experimental
f	friction
i	temporal counter of temperature recording
m	thermocouple number
Mod	modified
nTu	non-turbulent
Tu	turbulent
y	yield stress

Superscripts

k	iteration number

Different heat transfer modeling has been used for heat generation estimation of FSW [1]. Russell and Shercliff [3], Feng and Gould [4] proposed preliminary thermal models in this field. Ulysse used three dimensional finite element methods (FEM) for modeling of friction stir welding process [5]. Song and Kovacevic [6] introduced moving coordinate to reduce the difficulty of modeling; heat input from the tool shoulder and the tool pin. Some of researchers considered computational fluid dynamics (CFD) approach to simulate the process [7]. Besides the numerical modeling efforts, comprehensive analytical estimation of heat generation during FSW has been proposed [8]. However, it could not be used for practices due to difficulty of imposing immeasurable parameters. Moreover, experimental investigations of friction stir welding were reported for aluminum alloys [9].

Precise evaluation of heat input and proposes appropriate parameters were on the agenda for thermal analysis of experimental process. Heat input plays important role on the investigation of post-process parameters. Inappropriate handling of process may cause excessive or inadequate heat input and leads to welding defects. Controlling the heat response within the process would be possible by adjusting of the normal force, transverse speed, rotation speed, and cooling performance. Coupled numerical and experimental analysis identifies appropriate governing parameters [10]. These types of procedures became a novel study in friction stir modeling. Buffa et al. [11] proposed shear coefficient determination during FSW process using experimental measurements. In this connection, inverse heat transfer (IHT) problems' approaches are helpful to analysis of wide range of thermal processes using experimental measurements [12]. Results obtained using IHT approaches were deducted to design, optimization, estimation, identification, etc. [13–15]. Inverse analysis of each phenomenon due to applying of measurements gives reliable results. By using of measureable thermal quantity, e.g. temperature, it would be possible to obtain unknown and immeasurable quantities somewhat precisely. Therefore, some researchers chose inverse techniques for microstructural analysis of manufacturing, machining, and welding processes [16]. As to thematic similar work, Yang [17] proposed inverse determination of heat input within FSW process. This study considered the temperature of workpiece to be known by evaluation of melting temperature of pin at specified position at workpiece. The analysis culminated to recommendation of appropriate heat generation and welding sequence within joining process. However, the obtained heat maybe impractical for ordinary FSW and effect of involving factors like slip were not accounted in. To summarize, neglecting slip remains ambiguities in physical sense of real process and pin and shoulder interfaces were not oriented. Meanwhile, as to the important role of simultaneous cooling during welding, there was not any coverage to recommend online cooling performance. In the literature, optimization of parameters for experimentally investigated processes has not been covered for linear friction stir welding especially using inverse approaches. In this connection, this study proposes an inverse determination leads to optimization of experiments performed with different configuration of cooling.

The conjugate gradient method (CGM) was selected as an inverse approach to determine effective governing coefficients of generated heat during FSW process either with cooling stage or without it. To evaluate heat generation due to plastic deformation, slip function was defined. Slip was characterized by velocity difference of matrix and tool in exponential function form. Defining velocity profile in terms of time made the concept of slip more comprehensible and offered more stable solution for inverse