Journal of Manufacturing Processes 24 (2016) 186–194

Contents lists available at ScienceDirect

Journal of Manufacturing Processes

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

Calculating the energy required to undergo the conditioning phase of a titanium alloy inertia friction weld

R.P. Turner [a,*], D. Howe [b], B. Thota [a], R.M. Ward [a], H.C. Basoalto [a], J.W. Brooks [a]

[a] PRISM[2] Research Group, Metallurgy & Materials, University of Birmingham, Birmingham B15 2TT, UK
[b] Rolls-Royce plc, Materials & Process Modelling, PO Box 31, Derby DE24 8BJ, UK

ARTICLE INFO

Article history:
Received 20 May 2016
Received in revised form
19 September 2016
Accepted 21 September 2016
Available online 30 September 2016

Keywords:
Mechanics
Kinetic
Thermal
Equilibrium
Ti-6Al-4V
Analytical

ABSTRACT

Inertia friction welding (IFW), a type of rotary friction welding process, is widely used across aerospace, automotive and power-generation industries. The process considers a specialist rotary friction welding machine, which asks for the critical process parameters of inertial mass, initial rotational speed and applied pressure, to complete the relevant weld. The total kinetic energy available to the system can be calculated from basic physical relationships for the kinetic energy stored in a flywheel. This kinetic energy must be converted partly to heating the specimen at the interface, and partly to mechanical work via deformations. A finite element (FE) numerical model has been developed to predict the steady-state thermal profiles formed at the onset of mechanical deformation. Therefore, the amount of this total available energy for the process which is applied to the heating of the component at the interface through frictional contact has been estimated. Thus, the available energy left to produce the mechanical deformation via the flash formation can be calculated by subtracting the thermal energy from the total energy. This is of importance to the manufacturing engineer. A method of validating the FE modelling predictions was proposed using high-speed photography methods during the process to understand the rotational speed of the moving part at the instant that the steady-state deformation commences. Results from FE modelling and experiment suggest that the width of the steady-state thermal profile formed through the IFW, and the time taken to reach steady-state is strongly dependent upon the applied pressure parameter.

1. Introduction

Rotary friction welding is an advanced joining process, whereby two components with axial symmetry at the weld joint can be bonded using heat generated solely from the frictional interface caused by relative motion between the two [1]. A so-called inertia friction weld (IFW) is a type of rotary friction weld process, whereby kinetic energy stored in a rotating flywheel is converted into frictional thermal energy to mostly join two components of cylindrical geometry. One component is clamped to the rotating flywheel, whilst the other component is clamped in a non-rotating tooling, connected to a hydraulic ram [1]. During welding, the flywheel is brought to a certain rotation speed and a forging pressure is applied to the hydraulic ram to bring the two components to contact. The flywheel rotational velocity starts to decelerate owing to the conservation of the stored energy into thermal energy, causing the temperature to increase sharply at the interface owing to the generated friction [1]. The relative motion at the interface allows for a heating and plasticisation of the interfacial material, and large deformations—characterised by the distinctive flash formation associated with a rotary friction weld. Friction welding processes, typically the IFW process considered in this work and linear friction welding, are often described as consisting of a number of different "stages" or "phases" of the process. The conditioning phase is defined as the initial phase whereby heat is generated from solid friction between one stationary and one moving part [2]. During the conditioning phase no bulk deformation is observed, simply the flattening of surface asperities. Following the conditioning phase, the equilibrium phase sees weld line material extruded as flash, as a thermal equilibrium is achieved [2].

The process of IFW differs from the more commonly used Direct-drive rotary friction welding (DDRFW) simply in the mechanics of delivering the kinetic energy to the one side of the rotating component as it is joined with a stationary counterpart. Whilst the commonly used DDRFW process uses an electric motor to drive the rotating part at a constant rotational velocity, the IFW process uses

* Corresponding author.
E-mail address: r.p.turner@bham.ac.uk (R.P. Turner).

http://dx.doi.org/10.1016/j.jmapro.2016.09.008
1526-6125/

Table 1a
Weld parameters used for the series of nine FE models set-up.

Weld No.	Inertia, I ($kg\,m^2$)	Init. rotation speed, ω (rad/s)	Pressure, P (MPa)	Tot. kinetic energy, $E_{rot} = 0.5I\omega^2$ (J)	Angular momentum, $L_{rot} = I\omega$ (kgm^2s^{-1})
1	18.6	185	100	318,292½	3441
2	18.6	185	40	318,292½	3441
3	18.6	185	80	318,292½	3441
4	18.6	185	120	318,292½	3441
5	18.6	185	150	318,292½	3441
6	18.6	160	100	238,080	2970
7	18.6	135	100	169,492½	2511
8	18.6	115	100	122,992½	2139
9	18.6	100	100	93,000	1860

Table 1b
Experimental validation of FE model to predict energy consumed to form thermal profile during conditioning.

Weld No.	Total kinetic energy $E_{rot} = 0.5I\omega^2$ (J)	FE/analytic predicted energy to form thermal profile (J)	FE/analytic predicted rot. speed remaining (rad/s)	Measured[a] energy to form thermal profile (J)	Measured[a] rot. speed remaining (rad/s)	Numerical modelling error[b] (%)
1	318,292½	94,090	155.3	106,805	150.8	−11.9
2	318,292½	174,490	124.3	194,872	115.2	−10.5
3	318,292½	103,306	152.0	124,106	144.5	−16.8
4	318,292½	79,950	160.1	88,765	157.1	−9.9
5	318,292½	81,013	159.7	Experiment not performed		
6	238,080	90,777	125.9	119,118	113.1	−23.8
7	169,492½	99,796	86.6	116,621	75.4	−14.4
8	122,992½	104,132	45.0	Experiment not performed		
9	93,000	98,432	0	Experiment not performed		

[a] *Note*: measurements are estimated from high-speed photography images.
[b] The modelling error calculated is of the predicted energy taken to form thermal profile.

a flywheel. This produces a velocity that is not constant during processing, but continually decreasing until the flywheel has used up all of the stored kinetic energy. In manufacturing terms, the DDRFW process is limited as electric motors with the capability to run at such high speeds and deliver the torque required would need to be huge. Realistically, only very small components can be joined with even modern DDRFW machines. Whereas, IFW machines on the other hand simply need a large flywheel which can be wound to store the required kinetic energy to join sizeable metallic parts through friction processing.

However, during an IFW process, the kinetic energy delivered from the flywheel, must be converted partially to heat (through frictional contact and material shear) and partially to mechanical deformation to form the axial shortening and extruded material (flash) formation. The amount of kinetic energy needed to be provided to the flywheel to produce a certain amount of mechanical deformation is therefore difficult to ascertain. A model to help predict the amount of energy that is consumed through thermal loading is of great use to the manufacturing engineer. Energy balance calculations can prove a useful method of determining how much energy has gone in to heating of a part, and therefore how much is left for the mechanical deformation of the part. Appealing to basic physical relationships, it is feasible to calculate how much energy is consumed to produce the steady-state thermal cycles present in the material at the onset of mechanical deformation. An understanding of how the various IFW process parameters influence the energy used to heat the part to its steady-state thermal cycle can then be drawn.

Finite element (FE) modelling of the IFW process has been studied and performed for a number of years, dating as far back as the 1990s [3–5]. Some of the more successful models [6–9] have conventionally considered the problem using a 2½ D modelling environment, whereby the model considers a cross section of the axi-symmetric problem, but also calculates the out-of-plane rotational velocity associated with the component. Previous FE models of the IFW process have generally considered the friction welding of steels [6] and of nickel superalloys [7–9] reflecting the common materials attached using this joining technology. Some models also considered the joining of two different materials (dissimilar welding) [5,6]. However, the technology is rapidly being considered and developed for a wider range of materials, including the common titanium alloy Ti-6Al-4V, which is frequently used within the aerospace industry. As a result, FE models are also being advanced and developed to consider the IFW processing of such materials [10].

2. Methodology

Experimental IFW joints using small testpiece specimens have been carried out at a selection of the process parameters considered here (see Tables 1a and 1b). The variations in the axial shortening caused by the mechanical deformation at the weld line is evidenced (Fig. 1), thus the energy supplied by the flywheel to the testpiece, which in turn gets converted in to mechanical work, must vary. It therefore becomes of great importance to be able to calculate the quantities of the total supplied flywheel energy required to; (a) form the thermal profile present throughout welding, and (b) leave a sensible amount of remaining energy available for mechanical work.

The presence of a steady-state thermal condition within a friction weld has been established within literature previously [11]. The steady-state condition applies to the "equilibrium" phase, when the generation of heat inputted in to the system by friction and shear methods balances out the heat leaving the weld joint in to the flash. If an assumption is made that the IFW joint reaches its thermal steady-state condition as the onset of mechanical deformation begins (mechanical deformation being the process of axial shortening and flash forming), then we can equate the