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Orbital friction welding as an alternative process for blisk manufacturing

U. Raab[a,*], S. Levin[a], L. Wagner[a], C. Heinze[b]

[a] Institute of Materials Science and Engineering, TU Clausthal, Agricolastr. 6, 38678 Clausthal-Zellerfeld, Germany
[b] Rolls-Royce Deutschland Ltd & Co. KG, Eschenweg 11, Dahlewitz, D-15827 Blankenfelde-Mahlow, Germany

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ABSTRACT

Linear friction welding (LFW) is used for the production of compressor blisks in modern turbine engines. Orbital friction welding (OFW) performs a circular motion in contrast to the linear motion applied during LFW. In order to display the influence of the different kinetics on the heat generation, both processes were compared using identical process parameters. The tests were performed on multi-orbital friction welding machine in the force–displacement mode. In a frequency range from 28 to 56 Hz the time necessary to achieve a displacement of 5 mm was measured for both processes. Using Ti–6Al–4V as the test material, it is shown that with similar welding parameters, shorter welding times are achieved with OFW. The reason for the faster heat generation is a continuous relative speed, higher contact pressure and a larger distance covered within one cycle of the process.

1. Introduction

Linear friction welding was developed to apply the beneficial properties of rotary friction welds on non-axially symmetric components. This process was adapted for manufacturing of blade integrated disks used in turbine engine industries. The use of LFW for joining the titanium alloys Ti–6Al–4V and Ti–6Al–2Sn–4Zr–6Mo has been studied and has already developed into a state of the art process. Recent developments focus on the combination of nickel alloys and even nickel based single crystals for high-pressure compressor or turbine stages, respectively.

Linear friction welding of Ti–6Al–4V was firstly described by Vairis and Frost (1999). The authors examined the extrusion stage of the friction welding process and concluded that plastic material is extruded discontinuous. They defined four stages of the LFW process and developed a model to describe the material flow. In a subsequent paper Vairis and Frost (1999) defined a power input parameter for LFW that implies the parameter frequency, amplitude of oscillation, friction pressure and the cross-sectional area. Additionally, they developed a heat flow model and proved its feasibility by using the example of Ti–6Al–4V. Wanjara and Jahazi (2005) varied frequency, amplitude, pressure and axial shortening in the LFW process to classify the influence of these parameters on the welding behavior of Ti–6Al–4V. By adapting the power input parameter of Vairis and Frost, they showed that a critical heat input must be reached to produce sound welds without pores or oxides. Karadge et al. (2007) investigated the texture development in Ti–6Al–4V in linear friction welds. They found a change of the texture in the plastically affected zone caused by the flow of material along the reciprocating direction. Guo et al. (2012) used LFW to combine Ti–6Al–4V and Ti–6Al–2Sn–4Zr–6Mo and showed that LFW is capable to produce sound dissimilar welds. Apart from welding Ti–6Al–4V LFW is also used to combine other Titanium alloys and nickel based superalloys. In another work Guo et al. (2013) used LFW to produce similar Ti–6Al–2Sn–4Zr–6Mo welds and analyzed the influence of post weld heat treatment on the microstructure development in the weld zone. Vishwakarma et al. (2010) combined Allvac 718 Plus using LFW. They showed that LFW is capable to generate integral welds without oxides or particles at the weld line but found liquation at grain boundaries. Amegadzie et al. (2012) joined conventionally cast IN 738 and single crystal CMSX 486 superalloys and found liquation of various phases and oxides on the weld lines in both materials.

Abbreviations: a, amplitude; A_0, cross sectional area; f, frequency; F_F, friction force; F_N, normal force; P, power; Q, surface power density; v_r, relative speed; μ, friction coefficient; ω, circular frequency.

* Corresponding author. Tel.: +49 5323 72 3592; fax: +49 5323 72 2766.
E-mail addresses: ura@tu-clausthal.de (U. Raab), Sebastian.levin@tu-clausthal.de (S. Levin), lw@tu-clausthal.de (L. Wagner), Christoph.Heinze@Rolls-Royce.com (C. Heinze).

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As reported in the cited literature, LFW is capable of producing high quality titanium joints with similar and dissimilar alloy combinations. Problems with oxide films and liquation occur with Nickel base superalloys. Titanium friction welds can be characterized by a fine grained microstructure without oxides, inclusions or discontinuities. Depending on the welded alloys, the strength of the weld can surpass the strength of the parent material or can be improved by post weld heat treatment as reported by Guo et al. (2013).

Linear friction welding machines are based on rotary friction welding machines, whereby the spindle is replaced by a hydraulic actuator that generates the linear reciprocating motion as described by Kallee et al. (2003). The orbital friction welding machine used in this work is equipped with two rotating heads which perform the circular motion as reported by Zech et al. (2009) and Zech and Cramer (2009) respectively. The different mechanics are expected to have influence on the heat generation and the development of the weld. In contrast to the observations of Vairis and Frost (1999) where plastic material is extruded discontinuously along the linear reciprocating direction during LFW, the plasticized material is extruded continuously during orbital friction welding (OFW). Karadge et al. (2007) pointed out the influence of the reciprocating motion on texture and residual stresses in the weld plane. Since OFW conducts a circular motion a lower anisotropy of texture and residual stresses are expected. The influence of the different relative motion on the heat generation is presented in this paper.

2. Theory

The friction welding process was divided in four stages by Vairis and Frost (1999).

Phase I: In the initial phase, the true contact area increases due to asperity wear, leading to heat being generated by solid friction.

Phase II: In the transition phase, the material softens due to frictional heat. Large wear particles are expelled from the surface until the contact area increases up to 100%. Phase two ends when the material is no longer able to support the axial load.

Phase III: In the equilibrium phase, the soft material is extruded out of the welding zone under the formation of flash. The layer below the extruded material is plasticized simultaneously and is extruded in the next cycle. In this phase, additional heat is generated by breaking and reforming of bonds and plastic deformation.

Phase IV: In the deceleration phase, the relative motion is stopped. The forging force is applied and the remaining plasticized material is extruded to consolidate the weld and homogenize the microstructure.

These four phases take place in both orbital and linear friction welding, even though the kinematics of the two processes are different. Therefore, the heat generation during the first two phases can be compared.

During sliding of the welding partners heat is generated by solid friction. Vairis and Frost (2000) defined a power input parameter for linear friction welding that implies the parameter frequency, amplitude of oscillation, friction pressure and the cross-sectional area.

The power P generated by solid friction is the product of the friction force F_F and the relative speed v_R.

$$P = \mu F_N v_R = F_F v_R [\mathrm{W}] \tag{1}$$

The friction coefficient depends on temperature, and in this study, it is assumed that the development of the friction coefficient is equal for both OFW and LFW processes. Therefore, the value for the friction coefficient is set to 1 to simplify the model.

Table 1
Test parameters.

Friction phase		Forging phase	
Force [kN]	5	Force [kN]	10
Displacement [mm]	5	Time [s]	10
Frequency [Hz]	28–56		

Assuming that the frictional energy is completely transformed into heat, the surface power density Q can be described as the power P divided by the cross-sectional area A_0 of the test specimen.

$$Q = \frac{P}{A_o} = \frac{F_F v_R}{A_o} \left[\frac{\mathrm{W}}{\mathrm{m}^2}\right] \tag{2}$$

This general equation must be adjusted to distinguish between linear and orbital friction welding. The difference between both processes is the relative speed v_R which depends on the distance covered within one period of the relative movement. This is expressed in Eqs. (3)–(5) where ω is the circular frequency, a the amplitude of oscillation and f the frequency.

$$v_{LFW}(t) = \left| -\omega \sin(\omega t) \right| a \tag{3}$$

$$v_{OFW} = \omega a \tag{4}$$

$$\omega = 2\pi f \tag{5}$$

To achieve comparable conditions and perform both welding processes with the same amplitude of oscillation, both rotating heads must be used. Therefore a factor of 2 was included in the relative speeds.

3. Experimental procedure

Orbital and linear friction welding was performed on a multi-orbital friction welding machine with a maximum load of 100 kN. The machine is equipped with two rotating heads with a maximum frequency of 100 Hz and an oscillating circuit radius of 0.75 mm. The heads are positioned opposite to each other. The rotating direction of the heads is adjustable which enables the machine to perform both linear and orbital friction welding. A circular relative movement can be achieved when the rotating direction of the two heads is the same, while a linear relative movement is obtained when the heads are rotating in inverse direction.

The LFW and OFW tests were performed in the force–displacement mode. A final forging phase was applied after the predetermined displacement was reached. Five tests per process were carried out, using five different frequencies. The welding area was 98 mm^2. The process parameters are listed in Table 1.

4. Results and discussion

The multi-orbital friction welding machine records the development of force and displacement over time, making it possible to analyze the duration of the friction phases for all frequencies. The results are shown in Fig. 1.

In the tested frequency range the welding time decreases with increasing frequency. The curves tend to converge at high frequencies. The friction times for the OFW process are shorter than those obtained during the LFW process. With the lowest applied frequency of 28 Hz, the friction time with LFW is approximately 2.5 times longer. To achieve a comparable friction time, the LFW must be performed with double the frequency.

Fig. 2 displays axial shortening in the forging phase (Phase IV) in dependency of the frequency. The forging displacement increases with increasing frequency. The forging displacement for the OFW process is higher than those obtained during the LFW process. More