Joining Force of Heterogeneous Titanium Alloy in Linear Friction Welding Process

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Abstract: A dynamometer was designed and manufactured to measure the joining force in the linear friction welding process. The error percentages of the dynamometer in the upset (x) and vibration (y) directions were 0.9% and 0.75%, respectively. The cross-sensitivity range of the dynamometer was 1.2%—3.3% in the two directions. The precision level satisfies the requirements of the dynamometer test. The joining force of the TC17 and TC11 heterogeneous titanium alloys in the linear friction welding process was used to test the manufactured dynamometer. The test results showed that the upset force was large, but the vibration force showed a smaller change in TC11 during the linear friction welding process. In addition, the upset and vibration forces of the linear friction welding were greater with a short welding time than those with a long welding time.

Key words: heterogeneous titanium alloy; linear friction welding; dynamometer; upset force; vibration force

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0 Introduction

Linear friction welding involves joining two surfaces in contact with each other at a certain pressure and vibrating them at a certain frequency and amplitude to produce a reciprocating movement in a straight line. This generates friction heat to join the surfaces[1-5].

Linear friction welding is a new type of solid phase joining technology and has a series of unique advantages. It can be used to join dissimilar alloys and is widely used in the automotive and aerospace fields[6-8]. Linear friction welding can join heterogeneous metals and is an important method to develop double alloys for high-performance blisks in compressors and turbines. Currently used by engine companies in USA, UK, and Germany, linear friction welding technology is mature. Linear friction welding has been applied to manufacture titanium alloy aeroengine blisks[7].

At present, research on linear friction welding technology has mainly focused on the linear friction welding process, joining region microstructure, and joining region performance[9-15]. There are few reports in the literature on measuring the joining force in the linear friction welding process. A dynamometer was designed and manufactured to measure the joining forces of a TC11 and TC17 heterogeneous titanium alloy during the linear friction welding process. These findings will provide basic data for manufacturing blisks from heterogeneous titanium alloys by linear friction welding.

1 Design of Special Dynamometer for Linear Friction Welding

The elastic element of the dynamometer comprises an octagonal ring body. Resistance strain gages are placed at suitable locations on the ring body. When a force deforms the ring body,

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the strain gage resistance also changes. The data acquisition instrument collects the signal with an electrical bridge circuit, and the strain of the octagonal ring is measured to calculate the force. The width b, thickness t, and round radius r of the octagonal ring are obtained as follows

$$\sigma_z = E\varepsilon_z = E \times \frac{\eta_1 F_z r}{Ebt^2} = \frac{\eta_1 F_z r}{bt^2} \leqslant [\sigma_z] \quad (1)$$

$$\sigma_x = E\varepsilon_x = E \times \frac{\eta_2 F_x r}{Ebt^2} = \frac{\eta_2 F_x r}{bt^2} \leqslant [\sigma_x] \quad (2)$$

$$\sigma_y = E\varepsilon_y = E \times \frac{\eta_3 F_y r}{Ebt^2} = \frac{\eta_3 F_y r}{bt^2} \leqslant [\sigma_y] \quad (3)$$

The size of the dynamometer is determined according to the sizes of the workpiece and actual linear friction welding equipment. Fig. 1 shows the detailed design drawing.

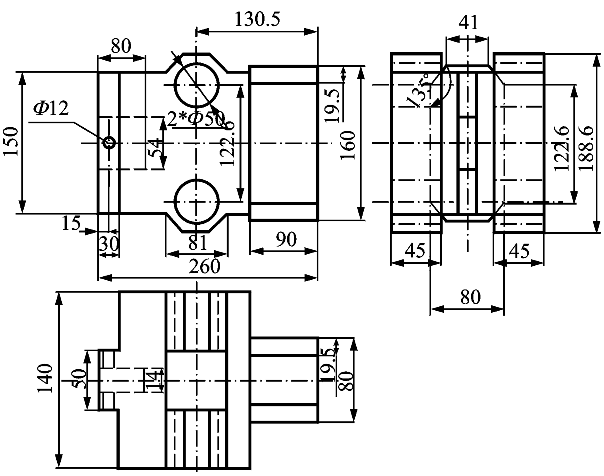

Fig. 1 Design drawing of the dynamometer for linear friction welding

2 Special Linear Friction Welding Dynamometer Calibration

The main principle of the linear friction welding dynamometer is to indirectly measure the external load that causes the micro-strain of the octagonal ring for obtaining the joining force. Thus, the dynamometer needs to be calibrated with the actual measured joining force. The linear friction welding dynamometer on the experimental platform was calibrated with hydraulic cylinders and the weighing sensor, as shown in Fig. 2. In the calibration process, different fixed methods were adopted for loads in different directions[16]. The calibration range of the linear friction welding dynamometer in the upset force (x) and vibration force (y) directions were 3 000×9.8 and 1 200×9.8 N, respectively. Fig. 3 shows the results. The error percentages in the x and y directions are 0.9% and 0.75%, respectively, as presented in Table 1. The cross-sensitivity range in the two directions was 1.2%—3.3%, as given in Table 2. Thus, the dynamometer meets the design requirements.

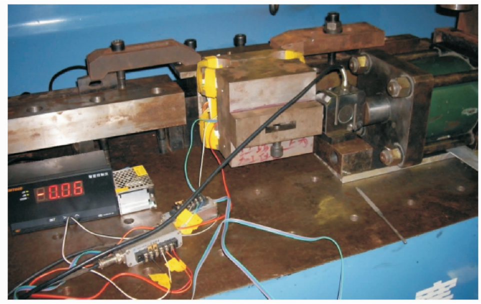

Fig. 2 Linear friction welding dynamometer calibration device

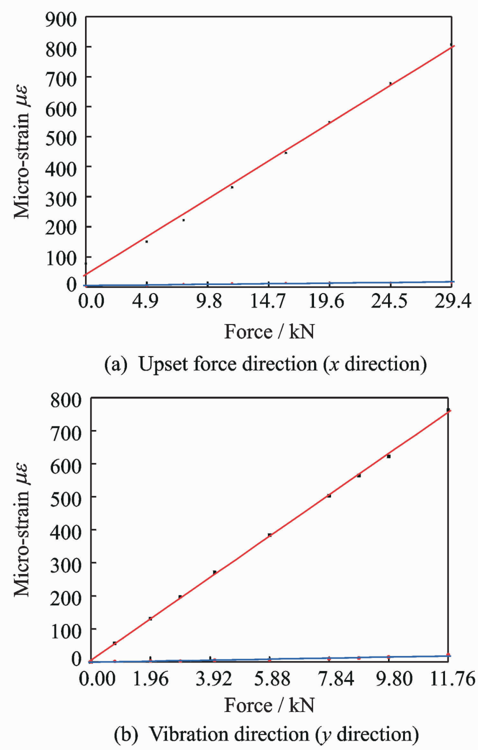

Fig. 3 Calibration curves of linear friction welding dynamometer

Table 1 Linear test results for the linear friction welding dynamometer

Load direction	Load/kN	Test micro-strain $\mu\varepsilon$	Calibration micro-strain $\mu\varepsilon$	Error/%
x	4.9	150.0	151.3	0.90
y	4.9	320.1	322.5	0.75

Table 2 Cross-sensitivity test results for the linear friction welding dynamometer

Load direction	Load/kN	Test micro-strain $\mu\varepsilon$		Average error/%	
		X	Y	X	Y
x	4.9	150	5		3.3
y	4.9	4	320.1	1.2	

3 Experiment to Test Joining Force of Linear Friction Welding

The TC17 and TC11 titanium alloys were employed in the linear friction welding experiment. The specimen size was 45 mm × 51.5 mm×51.5 mm.

The linear friction welding forces were measured with the specially designed and manufactured dynamometer. The four octagonal rings were the main part used to measure the forces. The dynamometer was clamped to the linear friction welding machine.

The process to measure the joining forces of linear friction welding is as follows. The vibration specimen was clamped to the vibration end, and the other specimen was clamped to the dynamometer. The dynamometer was fixed for the linear friction welding. The position accuracy of the specimen was guaranteed by the precision of the linear friction welding equipment, fixture, and dynamometer. Table 3 presents the linear friction welding experimental parameters.

Table 3 TC11-TC17 linear friction welding experimental parameters

Frequency f/Hz	Friction pressure P_1/kN	Upset pressure P_2/kN	Upset time t_1/s	Amplitude A/mm	Joining time t_2/s	Vibration end
40	0.74	1.5	4.5	4	4	TC17
						TC11
					3	TC17
						TC11

4 Experimental Results

Fig. 4 shows photos of TC11-TC17 joining by linear friction welding under different processing parameters. At the beginning of the joining, the upset and vibration forces were zero. The upset force produced by the hydraulic cylinder caused a wave curve. Then, the workpiece at the vibration end started to move up and down from the reciprocating vibration. Figs. 5—8 show that the upset force remained basically unchanged during the vibration friction process, while the vibration force gradually increased to the maximum. During the upset process, the upset force quickly reached a maximum value that it maintained for the upsetting time before slowly and smoothly decreasing. At the same time, the reaction force in the vibration direction rapidly decreased due to the workpiece being joined at both ends. There were internal forces between the workpiece and fixture until the former was loosened, and the forces in the two directions went back to zero. Figs. 5,6 show that the upset force is smaller when TC17 is the vibrating end than the one when TC11 is the vibrating end, but the vibration force does not change. The main reason is that TC11 is less hard than TC17, so the joining pressure needed to be large. However, the friction joining the TC11 and TC17 surfaces remained the same, so the vibration force hardly changed. Figs. 7,8 show the results of the above analysis. The upset forces in Figs. 7,8 are bigger than those in Figs. 5,6. This was mainly due to the short joining time for Figs. 7, 8; the friction heat was lower, so the upset force was big. The vibration force shown in Figs. 7, 8 is large. This was mainly due to the short vibration time, low degree of material plasticization, and relative increase in friction resistance.

Fig. 4 Photos of TC11-TC17

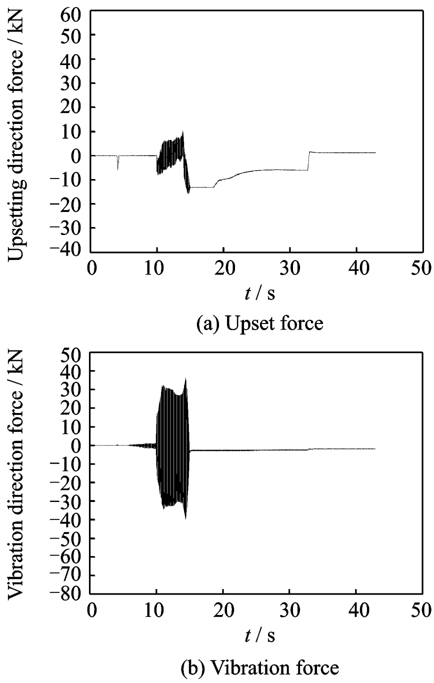

Fig. 5 TC11-TC17 linear friction welding curve (TC17 as the vibration end, 4 s joining time)

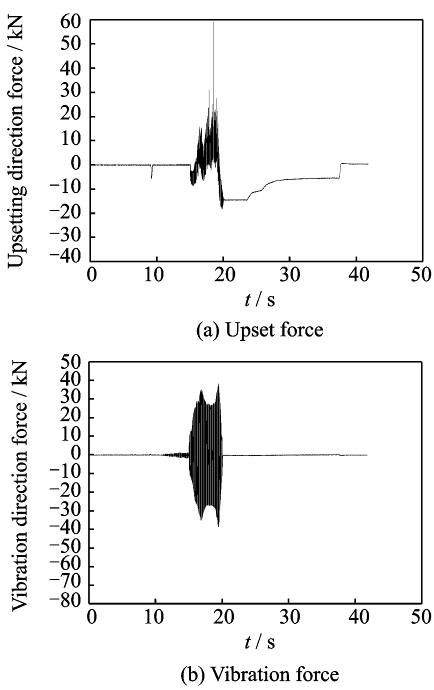

Fig. 6 TC11-TC17 linear friction welding curve (TC11 as the vibration end, 4 s joining time)

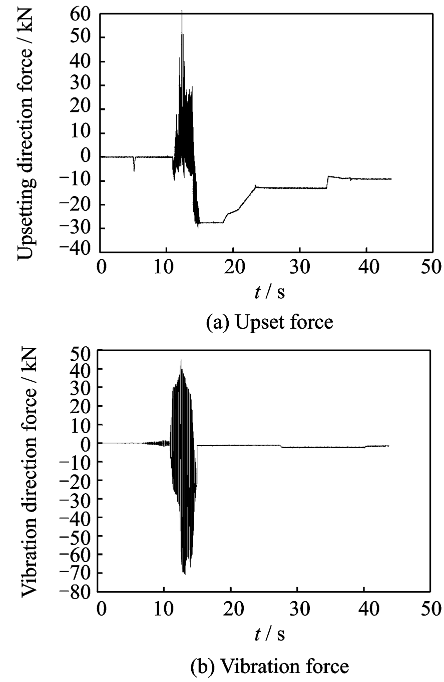

Fig. 7 TC11-TC17 linear friction welding curve (TC17 as the vibration end, 3 s joining time)

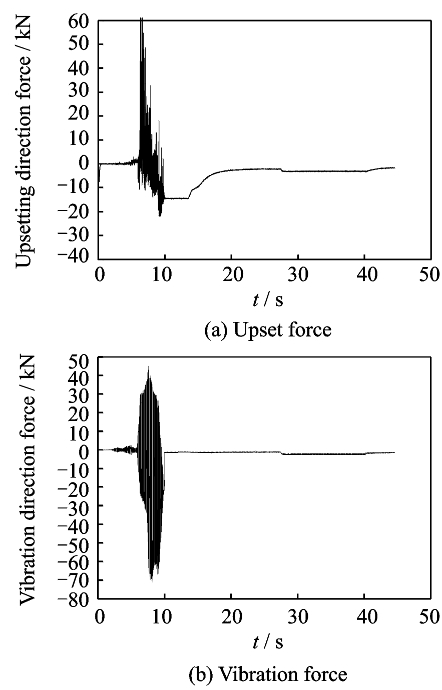

Fig. 8 TC11-TC17 linear friction welding curve (TC11 as the vibration end, 3 s joining time)

5 Conclusions

(1) A device suitable for measuring the forces of linear friction welding was designed and manufactured. After calibration, its error percentages in the x and y directions were 0.9% and 0.75%, respectively. The cross-sensitivity range in the two directions was 1.2%—3.3%.

(2) The measured results of the dynamometer showed that the upset force generated by linear friction welding was significantly greater when TC11 was the vibration end than the one when TC17 was the vibration end, but the vibration force did not change.

(3) The upset and vibration forces were greater with a short joining time than those with a long joining time.

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References:

[1] MA T J, LI W Y, YANG S Y, et al. Impact toughness and fracture analysis of linear friction welded Ti-6Al-4V alloy joints[J]. Materials & Design, 2009, 30 (6): 2128-2132.

[2] VAIRIS A, FROST M. Modeling the linear friction welding of titanium blocks[J]. Materials Science and Engineering A, 2000, 292(1): 8-17.

[3] LI W Y, MA T J, ZhANG Y, et al. Microstructure characterization and mechanical properties of linear friction welded Ti-6Al-4V alloy[J]. Advanced Engineering Materials,2008, 10(1/2): 89-92.

[4] WANG S G, BEN H F, HUANG Y, et al. Microstructure of Al-Cu-Li alloy joint with electron beam welding[J]. Journal of Nanjing University of Aeronautics & Astronautics, 2015, 47(5): 730-736. (in Chinese)

[5] SHAO Q, HE Y T, ZHANG P, et al. Influence of weld-induced plate distortion on compressive stability performance of friction stir welded aluminum alloy stiffened panel[J]. Journal of Nanjing University of Aeronautics & Astronautics, 2014, 46(6): 963-968. (in Chinese)

[6] BOEHLERT C J, MAJUMDAR B S, SEETHARAMAN V, et al. The microstructural evolution in Ti-Al-NbO+Bcc orthorhombic alloys[J]. Metall Mater Trans, 1999(30A): 2305-2323.

[7] Guo H Z, Zhao Z L, Wang B , et al. The effect of isothermal forging process parameters on the microstructure and the properties of TA15 near α Titanium ally[J]. Advanced Materials Research, 2007(26/27/28):367-371.

[8] LI S Q, ZHANG J W, CHENG Y J, et al. Current status on development of Ti3Al and Ti2AlNb intermetallic structural materials[J]. Rare Metal Materials and Engineering, 2005, 34(3): 104-109.

[9] VAIRI A, FROST M. High frequency linear friction welding of a titanium alloy[J]. Wear, 1998, 217(1): 117-131.

[10] MA T J, YANG S Q. Mechanical properties and microstructure features of linear friction welded TC4 titanium alloy joint[J]. Transactions of the China Welding Institution, 2007, 28(10): 17-20.

[11] ZHANG T C, LI J. Structure and mechanical properties of TC4 linear friction welding joint[J]. Transactions of the China Welding Institution, 2010, 31 (2): 53-56.

[12] LANG B, ZHANG T C. Microstructural evolution of a TC11 titanium alloy during linear friction welding [J]. Journal of Materials Science, 2010, 45(22): 6218-6224.

[13] XU H S, SHEN Y F, FENG X M, et al. Interface structure and properties on friction stir welding dissimilar alloys lap-butt joint of aluminum and stainless steel[J]. Journal of Nanjing University of Aeronautics & Astronautics, 2015, 47(3): 436-439. (in Chinese)

[14] ZHANG C C, HUANG J H, ZHANG T C, et al. Investigation on microstructure and microhardness of linear friction welded joints of dissimilar titanium alloys[J]. Transactions of the China Welding Institution, 2012, 33(4): 97-100.

[15] CHEN Z, LI Z, YU C. Hot deformation behavior of an extruded Mg-Li-Zn-Re alloy[J]. Materials Science and Engineering: A, 2011, 528(3): 961-966.

[16] LI Z F, CHAI Y, LI H F. Fault feature extraction method of vibration signals based on multi-fractal [J]. Journal of Data Acquisition & Processing, 2013, 28(1): 34-40. (in Chinese)

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