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Research Article

Energy Balance of the Linear Friction Welding Process

A. Medvedev[1], A. Vairis[2], R. Nikiforov[1] and A. Supov[3]

[1]Ufa State Aviation Technical University
[2] Dpt. of Mechanical Engineering, Technological Educational Institute of Crete, Heraklion 71004, Greece.
[3]Ufa Engine Industrial Association

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Abstract

The article is devoted to modeling the temperature field in the linear friction welding. The proposed method allows to estimate the fraction of thermal energy into the flash, and diverted a one-dimensional temperature distribution in the weld zone by using the theory of thermal processes of N. Rykalin.

Keywords: Linear friction welding, titanium alloys, temperature field modelling, energy balance

1. Introduction

The combined influence of temperature and plastic deformation during linear friction welding lead to changes in the structure of the weld and heat affected zone (HAZ), forming a residual stresses. The temperature field in the linear friction welding has been the subject of modeling in papers are used to estimate the temperature of the analytical solutions [1, 2] and the finite element method [3,4,5].

The dependence of the friction coefficient on temperature was used in most part of this papers for boundary conditions definition in the plane of contact welded parts.

This research attempted the boundary conditions in the plane of the welded joints based on the analysis of energy balance in the forming area of the weld joint. The distribution of heat is described analytical solution for the case of one-dimensional heat conduction.

2. Power balance components determination

Energy losses, produced by the hydraulic cylinders are contained on heating of the work pieces, flash, lost from the surfaces by convection and radiation mechanisms. Power losses are made up of heat inside the welded parts through the mechanism of thermal conductivity, the heat loss is from aside surface due to radiation and convection, and power losses with metal, extruded in to the flash. So, the equation of power balance has the form:

$$P_{inp} + P_{inp}^{'} = P_{out}^{\lambda} + P_{out}^{vol} + P_{out}^{surf} \tag{1}$$

where
P_{inp} - power input from oscillation hydraulic cylinder;
$P_{inp'}$- power input from shortening hydraulic cylinder;
$P_{out\lambda}$ – conductivity power looses;
P_{outvol} – power losses with metal, extruded in to flash;
$P_{outsurf}$ – power losses from surfaces by radiation and convection.

This paper estimating of the components in (1) using data recorded during the welding process. For comparable efforts, displacements of the shortening drive are small compared with the oscillation movement of the actuator, respectively $P_{inp'}$ is negligible compared with Pinp. Energy losses from the aside surface are also small compared with the other components of equation (1). Excluding $P_{inp'}$ and $P_{outsurf}$ equation (1) becomes:

$$P_{inp} = P_{out}^{\lambda} + P_{out}^{vol} \tag{2}$$

Power losses with metal, extruded in to flash, can be calculated by knowing the rate of shortening, and temperature of extruded metal:

$$P_{out}^{vol} = \frac{dz}{dt} \times A \times c\rho \times (T_{MEAN} - T_0) \tag{3}$$

where

$\frac{dz}{dt}$ – rate of shortening;
A – cross-section of welding samples;
cρ – volume heat capacity;
T_{MEAN} – mean temperature of extruded metal;
T_0 – room temperature.

* E-mail address: medvedevalexandr@inbox.ru
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Heat power, generated in the welded surfaces, can be calculated:

$$P_{inp} = F_t \times \frac{dx}{dt} \tag{4}$$

where

$\frac{dx}{dt}$ – speed of oscillation hydro cylinder;

F_t – shear force on the welded surfaces.

Shear force on the welded surfaces can be calculated:

$$F_t = F_X - m\frac{d^2x}{dt^2} \tag{5}$$

where

$\frac{d^2x}{dt^2}$ – acceleration of oscillation hydro cylinder;

m – mass of vibrating units;

F_X – the force, generated by oscillation hydro cylinder.

All components of (2) – (5) can be calculated in the attached diagrams LFW process, and given value T_{MEAN}.

Since the values of all parameters in (2) – (5) vary as close to sinusoidal, the value of the input power is averaged over the period of oscillations.

The value T_{MEAN} is unknown, and may vary at different stages of the process. In the proposed method the average temperature of extruded metal, is actually the initial approximation, it is considered to be constant during the entire welding process, and must be determined with iterative procedure.

3. Temperature field calculation

Calculated value of P_{out}^{λ}, determines the intensity of work pieces heating, and has been used for estimate the temperature field during welding. On purpose to that we used the calculation scheme of rod heating (one dimensional heat transfer).

In the process of friction welding heat is extracted to the plane of the contact pieces, and extends in a direction perpendicular to the plane of the joint. In this conditions, the heat propagation is described by the differential equation:

$$\frac{\partial T}{\partial t} = \frac{\lambda}{c\rho}\left(\frac{\partial^2 T}{\partial x^2}\right) - bT \tag{6}$$

In addition, the apparatus of mathematical physics allows to obtain analytical solutions. Thus, the solution of equation (6), as the case stands at time t = 0 in section of the rod with coordinate z = 0, the amount of heat Q enters instantly. The function is:

$$\Delta T = \frac{Q}{c\rho F\sqrt{4\pi at}} \exp\left(-\frac{z^2}{4at} - bt\right) \tag{7}$$

In order to obtain an expression describing the temperature field from the heat source current for a long time, the function (7) must be integrated over time. Thus, an equation describing the temperature distribution in the rod heated fixed 2-D heat source. The function is:

$$T = T_0 + \frac{1}{c\rho F\sqrt{4\pi a}} \int_0^t \frac{q(\tau)}{\sqrt{t-\tau}} \exp\left(-\frac{z^2}{4a(t-\tau)} - b(t-\tau)\right) d\tau \tag{8}$$

where

$q(\tau)$	–	The law of variation extracted power with time;
t	–	Heating time;
F	–	Cross-section of the rod;
a	–	Coefficient of thermal diffusivity;
b	–	Coefficient of heat transfer surface;
c	–	Heat capacity;
ρ	–	Density;
T_0	–	Initial temperature.

The temperature field in the heating stage in conditions without plastic flow of metal into the joint could be described by this equation (8).

Since the plastic flow in the joint distribution of heat in the workpiece is changed - the heat generated during friction and plastic deformation is transmitted not only deep into the workpiece due to heat, but carried away with the mass of the extruded metal flash. Therefore, this approach cannot be applied to calculate the temperature into the source of plastic deformation. However, the length of the source of plastic deformation in the direction perpendicular to the plane of the interface is small, the width of flash on the welding conditions for the welding of two-phase titanium alloys does not exceed 0.5 ... 0.6 mm, which is 0.25 ... 0.30 mm in one piece.

Obviously that the proposed approach makes it possible to calculate the temperature field, not only at the stage of heating, but also at the stage of material extrusion. In this case, velocity equal to the rate of precipitation must be assigned to the heat source.

The temperature distribution in the rod, heated by a moving heat source is described by the following equation:

$$T = T_0 + \frac{1}{c\rho F\sqrt{4\pi a}} \int_0^t \frac{q(\tau)}{\sqrt{t-\tau}} \exp\left(-\frac{(z - fz(\tau))^2}{4a(t-\tau)} - b(t-\tau)\right) d\tau \tag{9}$$

where

$fz(\tau)$ – The law of moving of the heat source.

The dependence on fz(t) has been accepted with according to the available experimental data on precipitation during welding.

4. Guess value of T_{MEAN} correction

In calculating the estimated temperature distribution T (z, t) and the width of the weld could be assessed S value of the selection T_{MEAN}. To do this it is essential to compare the magnitude of P_{outvol} in steady-state condition with the calculated value of thermal power diverted to the flash:

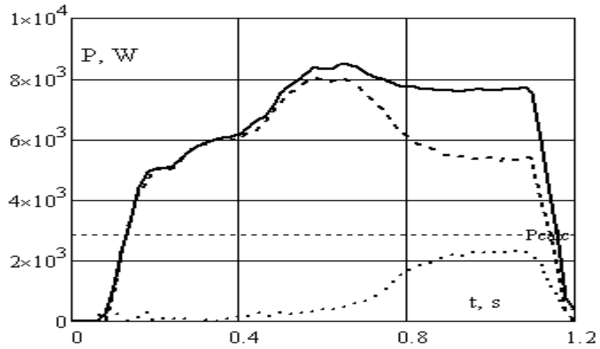
$$P_{CALC} = \frac{sdt}{dz} \times F \times c\rho \int_0^{s/2} (T - T_0) dz \tag{10}$$

The proposed method was used to calculate the temperature field for welding of three different combinations of welding cycles (attached table 1). In table 1 s is width of weld and h – value of shortening.

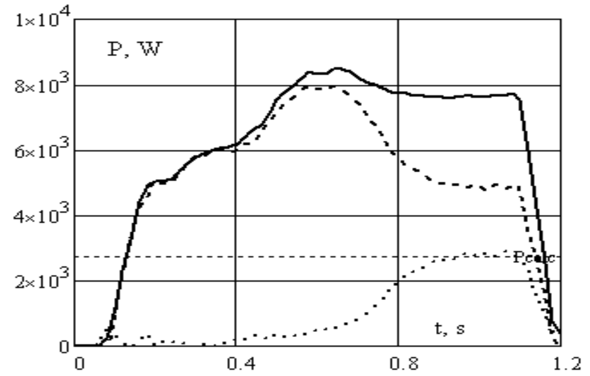
Table 1. Parameters of welding cycles.

	***a*, mm**	***f*, Hz**	**F_Z, kN**	***h*, mm**	***s*, mm**	**T_{MEAN}, K**
Welding cycle (a)	2,3	50	40	2	0,62	1300
Welding cycle (b)	2,0	50	35	2	0,65	1350
Welding cycle (c)	2,5	30	25	2	0.68	1350

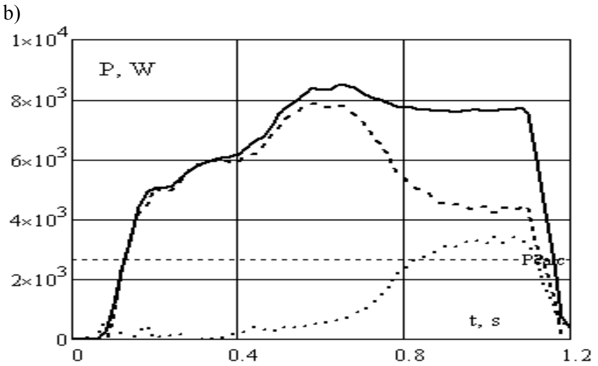
Curves of changes in components of the balance of power which are built for the investigated combinations of parameters are shown in Fig. 1. The value of P_{CALC} indicated on the graphs the dotted line. The results of calculation of temperature field during welding are shown in Fig. 2 and 3.



a)



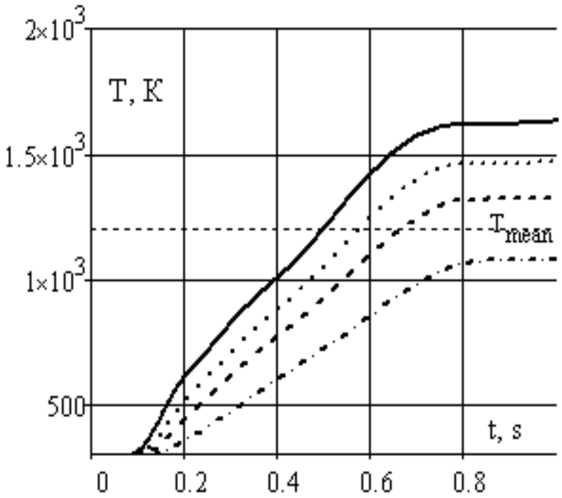
b)



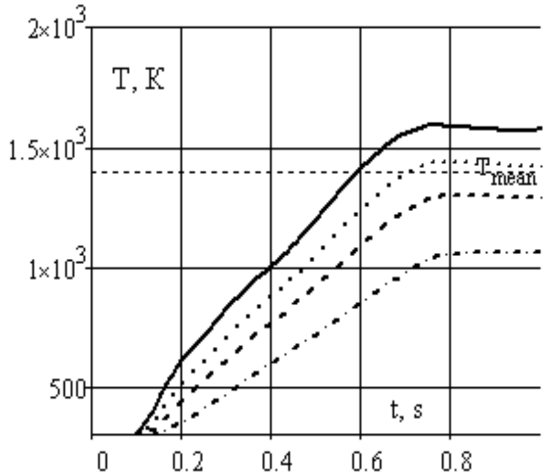
c)

___ power input
….. loses with metal extruded into flash
---- heat capacity expended for workpieces

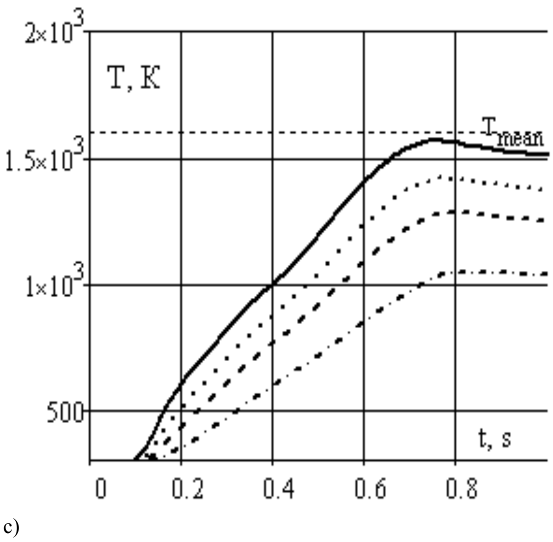
Fig. 1. Changing the components of the balance of power in equation (2) for the welding cycle with different combinations of welding parameters.



a)



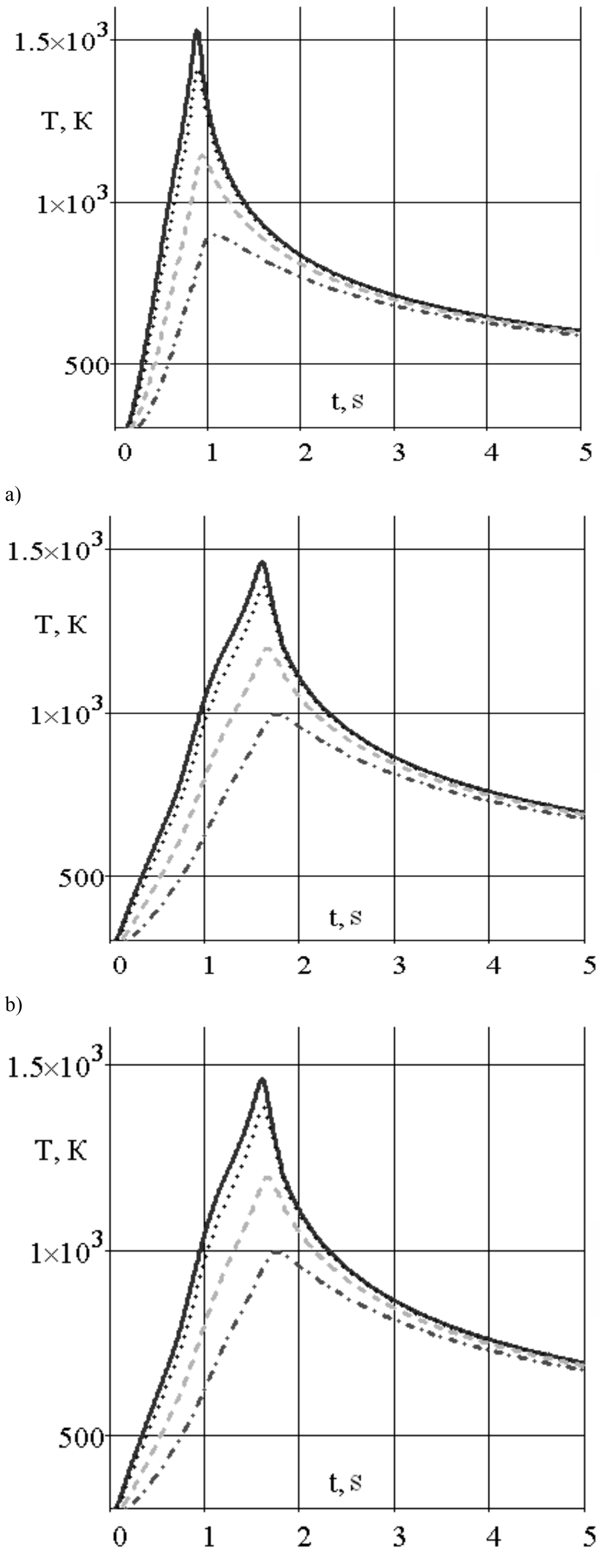
b)



c)

___ joint section;
…... 0.25 mm from joint section;
----- 0.5 mm from joint section;
-.-.- 1.0 mm from joint section;

Fig. 2. Changing the calculated temperature in cross-sections influence at the different distances from the plane of the joint for the welding with different values of the parameters of the welding parameters.



___ joint section;
…... 0.25 mm from joint section;
----- 0.5 mm from joint section;
-.-.- 1.0 mm from joint section;

Fig. 3. Thermal cycles of cross-sections located at different distances from the joint.

5. Temperature field modeling for various welding cycles

Welding cycles (a) and (c) correspond to extreme values of F_Z and a × f of the investigated range. As seen in Fig. 1 increase in the F_Z and a × f leads the increase in input power and reduce the welding time. As seen from the Fig. A variation in the temperature curves for linear friction welding is consistent with the accepted theory of thermal processes in the welding division of the whole period of under heating, quasi-steady state period and period of temperature equalization.

In case (a) at a lower value of the average temperature T_{MEAN} temperature in the plane of the interface was higher. This may be due to higher temperature gradients during welding on the "hard" welding cycles and the assumptions adopted in the calculation.

At the initial stage of the linear friction welding heat is caused primarily by friction in the joint, and the approximation of a 2-D heat source corresponds to the actual conditions. At the stage of steady draft, the dominant mechanism is the dissipation of mechanical energy during plastic deformation, heat in this case is allocated over the entire volume involved in a visco-plastic flow. The attached scheme is concentrated heat source, instead of distributed, gives overestimated values of the temperature in the welded junction, and in assessing the thermal state in the weld zone it is preferable to use the average temperature T_{MEAN}.

Summary and Conclusions

1. During the linear friction welding equilibrium is established between the energy input oscillations on the one hand, the energy output of the welding zone in the flash, and diverted to the work piece on the other hand. More than 1/3 of the input comes to the flash in the case of the investigated combination of parameter cycle.
2. Despite of the short duration of the cycle, during the welding process the processes under heating are going in time completely and quasi-stationary temperature field are installing.
3. The proposed method allows for the analysis of kinematic and force parameters, recorded during the linear friction welding, estimation of the fraction of thermal energy in the flash diverted, and a one-dimensional temperature distribution in the weld zone T (z, t).

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