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Research Article

A Two-Parameter 2D-Model of the Elastic Stage of Linear Friction Welding Using ANSYS Mechanical Finite Element Analysis Programme

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Abstract

A numerical model of the elastic stage of the linear friction welding process of α+β titanium alloy VT6 was developed. The ANSYS Mechanical software was used for modelling. Agreement between simulation results and experimental data, for the duration of the process until axial shortening begins, was reached using fitting parameters. It is shown that for the model to achieve a good quantitative agreement, only two parameters are necessary.

Keywords: linear friction welding, computational experiment, engineering software

1. Introduction

For the advancement of aviation industry new technologies are necessary to manufacture a new generation of gas turbine engines (GTE) in order to achieve greater thrust per pound of weight capacities. In particular, one way to get lightweight GTE units is the application of linear friction welding (LFW) technology to the manufacture of GTE blisks instead of milling them from solid blanks. LFW technology allows, also, the repair of damaged blades instead of replacing the whole assembly.

Linear friction welding (LFW) is a type of friction welding [1], in which a weld between parts is formed by applying a compressive force to them while moving in a reciprocating mode relative to each other.

There are four stages (phases) of the process LFW [2]. At the initial stage samples touch under pressure and their relative motion begins, which is accompanied by a reduction in surface roughness on the welding interface due to frictional wear. In the transition (elastic) stage there is heat produced by friction and elastic deformation of the samples. When plastic deformation occurs the equilibrium phase follows, characterized by axial shortening due to the displacement of plastic material from the contact zone to form flash. At the final stage (forging) mechanical motion is rapidly stopped and additional forging pressure may be applied to form a weld joint.

The formulation of accurate mathematical and computer models is the subject of this detailed study of this process. For simplicity the simulation of the LFW process is divided into several stages, and in this paper we will only consider the simulation of the elastic stage of LFW with a numerical model using the engineering package ANSYS Mechanical.

This model is based on experimental data and it will investigate the effect various parameters have on the duration of the elastic stage.

2. Problem formulation

The analytical simulation of the elastic stage of LFW is a complex problem, as it involves several physical phenomena:

1) heating and cooling processes, where the thermodynamics laws are applied;
2) elastic deformations (using the elasticity laws).

In the engineering package ANSYS Mechanical the relationship between laws of mechanics and thermodynamics is made by means of two mechanisms [3]. The first mechanism is the thermoelastic deformation, which deals with elastic deformation and thermal expansion and described in terms of internal stress tensor [4]:

$$\sigma_{ik} = -K\alpha(T - T_0)\delta_{ik} + K\varepsilon_{ll}\delta_{ik} + 2\mu\left(\varepsilon_{ik} - \frac{1}{3}\delta_{ik}\varepsilon_{ll}\right) \quad (1)$$

where α – coefficient of thermal expansion, K^{-1}; K – bulk modulus; Pa, μ – shear modulus, Pa.

Secondly, a connection is made with an external heat source f_{fr} in the heat equation describing heat generation due to friction. The friction law chosen in the model follows Amontons-Coulomb law:

$$\tau_{fr} = \lambda(T)P_n, \quad (2)$$

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where τ_{fr} – equivalent shear stress, Pa; $\lambda(T)$ – coefficient of friction, which depends on temperature; P_n – pressure, normal to the plane of movement (is equivalent to reaction force), Pa. An external heat source is given by:

$$f_{fr} = k_f \tau_{fr} v, \tag{3}$$

where k_f – the proportion of friction energy transformed into heat; v – speed of sliding, m/s.

A two-dimensional thermal-mechanical problem of the process between two rectangular samples with a cross-section area equal to 338 mm^2 is considered.

The upper sample is sliding on the surface of the lower sample with the top edge of the upper sample moving according to a sinusoidal law with frequency f and amplitude a,. Movement is applied gradually and is increasing linearly from zero to a maximum value A within t_0 = 0.1 s from start of process. This is similar to reality, as the actual movement of the rubbing specimens in the LFW machine is effected in a gradual manner. Samples are also compressed by a normal force, which increases linearly from F_0 =15 kN to F_1 at a rate of V_F = 100 kN/s. The bottom part of the lower sample is stationary.

The initial sample temperature is uniform at 293 K (room temperature). The process is considered adiabatic. The material model is considered to be isotropic elastic and the VT6 alloy properties [5, 6] are used. The friction coefficient $\lambda(T)$ follows a linearly increasing function of temperature, which is based on preliminary experimental results:

$$\lambda(T) = 0.3 + 5 \cdot 10^{-4} (T - 293). \tag{4}$$

3. Comparison with experimental data

For this experiment samples of titanium alloy VT6 (same basic composition as Ti-6Al-4V) were used. Welding was carried out at an LFW machine to ensure the correct application of the appropriate welding conditions.

For validation purposes the computer model is compared to experimental data. The duration t_s of the process before axial shortening begins (2nd phase) was selected as the target function Φ of numerical experiment. The criterion for beginning of axial shortening was chosen to be the coefficient k_p, which determines the fraction of nodes on the contact line, reaching yield stress.

The target function Φ depends on parameters of the welding process: normal force F_1, amplitude of oscillation A and oscillation frequency f. To estimate the influence of these parameters on Φ a two-level full factorial experiment of type 2^3 was designed. Machine operating limits of relative velocity limit the extent of variation that can chosen for frequency and amplitude when planning such an experiment. In this factorial design the variable parameters were chosen to be F_1, the product $A{\cdot}f$, and the oscillation period $1/f$.

The target function Φ is the elastic stage duration. This time is corresponds to the beginning of axial shortening due to deformation (in order to take into account the experimental error as the criterion was set to 1% of the initial specimen length shortening). The matrix of the designed experiments, for a range of welding parameters as well as the elastic stage time length (with its corresponding confidence interval) are shown in Tab. 1.

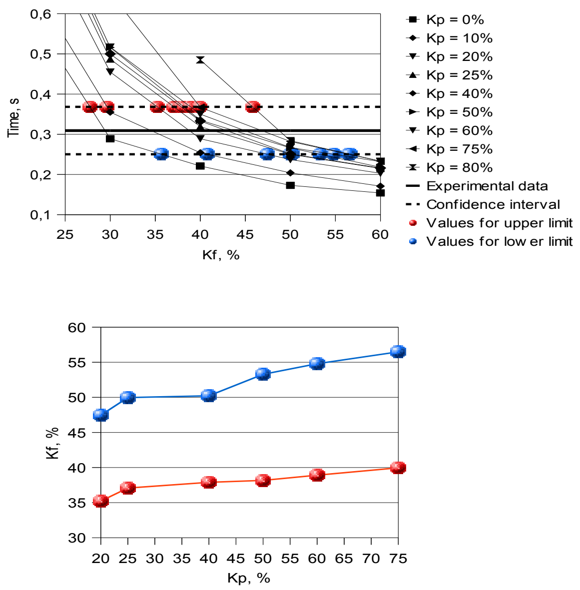
Table 1. The results of the factorial experimental design of welding alloy VT6.

Matrix of experimental design			Welding parameters			Elastic stage duration
$X1(F_1)$	$X2(A{\cdot}f)$	$X3(1/f)$	F_1, kN	A, mm	f, Hz	$t_s = t_o \pm dt$, s
-1	-1	-1	25	1.5	50	0,309 ± 0,059
1	-1	-1	40	1.5	50	0,399 ± 0,037
-1	1	-1	25	2.3	50	0,632 ± 0,059
1	1	-1	40	2.3	50	0,780 ± 0,025
-1	-1	1	25	2.5	30	0,352 ± 0,021
1	-1	1	40	2.5	30	0,378 ± 0,041
-1	1	1	25	3.8	30	0,591 ± 0,039
1	1	1	40	3.8	30	0,685 ± 0,081

During LFW energy produced by friction goes into heat and to smoothening of the surface roughness of the sample, so the model must take into account the parameter k_f – the proportion of friction energy transferred into heat (see Eq. (1)). Parameter k_f directly affects the quantity of heat and, hence the duration of the process before the onset of axial shortening.

In numerical experiments the target function Φ(A, f, F_1, k_f, k_p) was chosen. The parameters k_p and k_f were varied to achieve a match between the values of target function Φ and experimentally measured time interval t_s. As there is set of values (k_p, k_f) for each set of process parameters (A, f, F_1) modeling results need to be compared with actual experiments and therefore identify a common area in parametric space (k_p, k_f) which satisfies all experimental data.

From these modeling studies the dependence of the target function Φ on parameters k_p, k_f was obtained (Fig. 1a). Using a piecewise-linear interpolation for any value k_p a pair of values k_f was defined when the duration of the elastic stage Φ coincided with the upper ($\Phi_1 = t_0 + dt$) and lower ($\Phi_2 = t_0 - dt$) limits of the confidence interval t_s consequently. Showing this values on a graph in coordinates (k_p, k_f), two curves are obtained for the upper Φ_1 and lower Φ_2 limits of confidence interval. For any point of the area bounded by these curves the value of target function lies within the confidence interval t_s, so for corresponding values of k_p, k_f simulation results coincide with experimental data while taking into account the experimental error (see Tab. 1).



(a)

(b)

Fig. 1. The dependence of target function Φ on k_f for different values of k_p for f = 30 Hz, A = 3,8 mm, F_1 = 40 kN, and time length of second stage t_s from experiment (a) and constructed area of values (k_p, k_f) satisfying $\Phi \in t_s$ (b)

4. Analysis of the fitting parameters

To further increase the accuracy of the prediction of the parameters k_p and k_f, areas bounded by curves Φ_1 and Φ_2 in the parametric space *(k_p, k_f)* were constructed for all sets of parameters *A, f* and F_I from Tab. 1. Figure 2 shows clearly that it is practically impossible to determine the overall value of each fitting parameter for all sets of parameters. Therefore parameters *(k_p, k_f)* depend on values of *A, f* and F_I. As it can be seen there are two areas where there is an overlap. The main difference between these two areas is with value of the normal force F_I. The optimal value pairs (k_p, k_f) are near the interval between values (k_p = 25%, k_f = 38%) and (k_p = 60%, k_f = 42%) for F_I = 40 kN and between values (k_p = 0%, k_f = 44%) and (k_p = 40%, k_f = 49%) for a F_I = 25 kN. There is no dependence of parameters (k_p, k_f) on A and f, so $k_p = k_p(F_I)$ and $k_f = k_f(F_I)$. It should be noted that parameter k_f affects in a dominant manner the target function Φ.

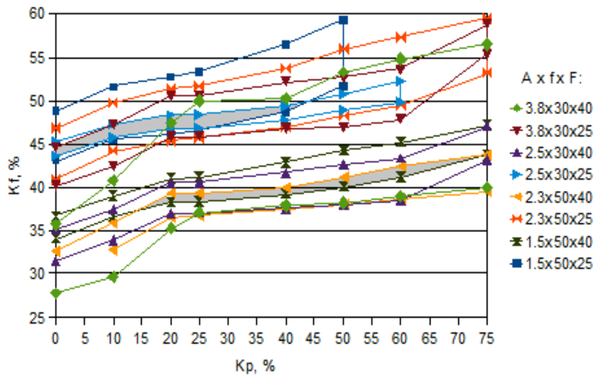


Fig. 2. Diagram of k_f vs. k_p for the set of factors (A, f, F_I) from Table 1, where $\Phi \in t_s$.

Based on these data there were the following functional dependencies between fitting parameters and normal force F_I (in kN):

$$k_p = \frac{1}{3}(5F_1 - 65)\%, \qquad k_f = \left(60 - \frac{1}{2}F_1\right)\%. \tag{5}$$

It should be noted, that parameter k_f depends significantly on force F_I. Decreasing F_I leads to an increase of k_p. This can be explained by the fact that with a higher value of normal force a larger proportion of frictional energy goes to reduce surface roughness of the sample. Following Eq. (5) parameter k_f cannot exceed 60% because of the lower limit of F_I necessary to achieve welding conditions for VT6. Consequently, it is necessary to investigate further the effect of low values of F_I. But for the range of force values studied, the fitting parameters, defined by Eq. (5), are in good quantitative agreement with experimental data as they are within the confidence interval of t_s.

5. Simulation results

The maximum values for temperature and stress are shown across the contact area, and as expected they change nonlinearly with space.

Figure 3 shows the distribution of temperature and stresses along the weldline for a normal force F_I = 25 kN and 40 kN for the f = 50 Hz, A = 1.5 mm case for t_s (t_s = 0.72 s for F_I = 25 kN, t_s = 0.62 s for F_I = 40 kN, t_s is estimated up to the middle of oscillation just before axial shortening begins).

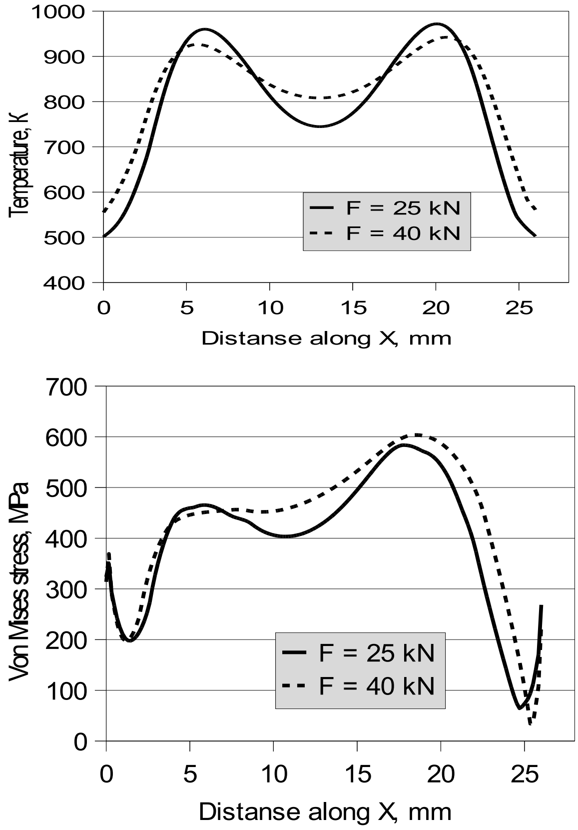


Fig. 3. The temperature and stresses distribution along the contact line for f = 50 Hz, A = 1,5 mm, (—) F_I = 25 kN at the t=0.72 s, (- -) F_I = 40 kN at the t=0.62 s

For larger values of normal force the distribution of stresses and temperature in the contact area becomes more uniform, while a smaller value of the normal force leads to a higher temperature gradient, indicating that plastic deformation will develop within smaller areas and not be across larger parts of the welding interface. Consequently, the developed numerical model of the elastic phase suggests that the use of larger normal forces in LFW is more preferable as it produces a more preferable uniform temperature field on the interface.

6. Conclusion

This paper shows that it is adequate to study only two parameters in order to achieve a good quantitative agreement between simulation results and experimental data. The functional dependence of the fitting parameters with normal force was determined, which lead to a model for a wide range of process parameters. This model can then be used as a basis for developing an adequate two-dimensional numerical model of the complete LFW process.

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References

1. V. I. Vill. Friction Welding of Metals. Moscow: Mashinostroenie, 1970. (in Russian)
2. A.Vairis, M.Frost. On the extrusion stage of linear friction welding of Ti6Al4V. Material Science and Engineering, **A271** , 477 (1999).
3. ANSYS Mechanical APDL Basic Analysis Guide. Release 13.0. ANSYS Inc., November 2010. [Electronic resource]
4. L. D. Landau, E. M. Lifshitz. Course of Theoretical Physics in 10 volumes. Volume 7. Theory of Elasticity. Moscow: Nauka, 1987. (in Russian)
5. GOST 19807-91: Wrought titanium and titanium alloys. Grades. Moscow: Standarts Publ., 1991. (in Russian)
6. Characteristics of titanium alloy VT6. Database of Steel and Alloys. (in Russian) URL: http://www.splav.kharkov.com/mat_start.php?name_id=1298 (access date: 19.10.2012)