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Testing and Modeling of Mechanical Characteristics of Resistance Welding Machines

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Abstract: The dynamic mechanical response of resistance welding machine is very important to the weld quality in resistance welding especially in projection welding when collapse or deformation of work piece occurs. It is mainly governed by the mechanical parameters of machine. In this paper, a mathematical model for characterizing the dynamic mechanical responses of machine and a special test set-up called breaking test set-up are developed. Based on the model and the test results, the mechanical parameters of machine are determined, including the equivalent mass, damping coefficient, and stiffness for both upper and lower electrode systems. This has laid a foundation for modeling the welding process and selecting the welding parameters considering the machine factors. The method is straightforward and easy to be applied in industry since the whole procedure is based on tests with no requirements for knowledge of the machine construction.

1. Introduction

The dynamic mechanical responses of welding machine have a significant influence on the quality of resistance welding, especially in projection welding when collapse of weld parts occurs. It is mainly governed by the mass, stiffness and damping capacity of various components of machine system.

In order to understand the influence of the mechanical dynamics of the welding machine on the welding process parameters and to more accurately simulate the welding process, it is necessary to determine the mechanical parameters of welding machines. Due to the coupling reactions of the components of machine system and the complexity of machine structure, it is very difficult to measure or calculate these parameters directly, and no test method has so far been presented in literature that can be easily applied in an industrial environment for building up the mathematical models of the welding machines.

In this paper, a mathematical model for characterizing the dynamic mechanical responses of machine is developed. A special test set-up called "breaking test set-up" is designed with which the movements of both electrodes and breaking load are measured simultaneously. By using the test results, the mechanical parameters of welding machine are identified, including equivalent mass, damping coefficient, and stiffness for both electrode systems.

2. Mathematical models for the mechanical properties

The mechanical system of resistance welding machine is simplified as a lumped parameter system assuming that the frame is rigid as shown in Fig. 1.

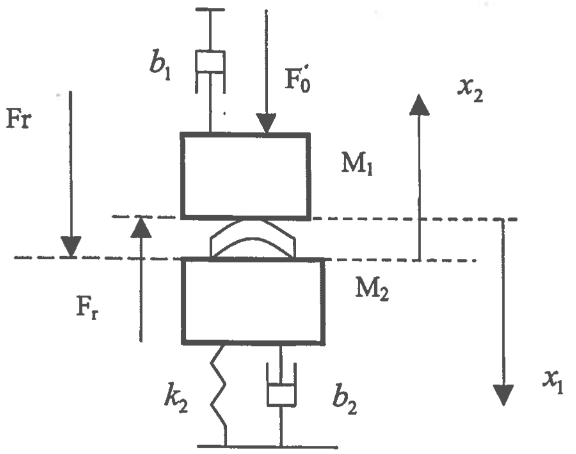


Fig.1 Mechanical model of resistance spot welding

In resistance welding, the work piece is pre-stressed by the electrode force, which is stabilized by the end of the squeeze phase, after the high current inputs in the weld stage, a movement of the electrodes toward one another in the direction of electrode force will take place due to deformation of work pieces or indentation of the electrodes into the materials as they soften or melt. The movement of upper electrode according to Newton's second law is thus described by the equation:

$$m_1\ddot{x}_1 + b_1\dot{x}_1 = F_0 - F_r \tag{1}$$

Where m_1 is the equivalent mass, b_1 is the equivalent damping coefficient of upper electrode system, F_r is the reaction force from the work piece, F_0 is the electrode force:

$$F_0 = F_{cylinder} + m_1 g$$

It has been proved that the variation of pressure in cylinder during the electrode movement can be neglected due to the fact that the electrode displacement is so small and the electrode speed is so fast that the supply system of cylinder is not able to follow the moving electrode, therefore, F_0 is considered as a constant.

Similarly, the movement of lower electrode is described by the equation:

$$m_2\ddot{x}_2 + b_2\dot{x}_2 + k_2 x_2 = -F_r \tag{2}$$

Where k_2 is the equivalent stiffness, b_2 represents the equivalent damping coefficient and m_2 stands for the equivalent mass of lower electrode system.

At the movement of splash in spot welding or collapse in projection welding, the reaction force from work piece equals to zero($F_r = 0$), thus equations (1) and (2) becomes :

$$m_1\ddot{x}_1 + b_1\dot{x}_1 = F_0 \tag{3}$$

$$m_2\ddot{x}_2 + b_2\dot{x}_2 + k_2x_2 = 0 \tag{4}$$

From Eqn.(3), we get:

$$\ddot{x}_1 + 2\xi\dot{x}_1 = \frac{F_0}{m_1} \qquad \text{(where: } 2\xi = \frac{b_1}{m_1}\text{)}$$

Its homogeneous form is:

$$\ddot{x}_1 + 2\xi\dot{x}_1 = 0 \tag{5}$$

Assume the solution of Eqn. (5) in the form: $\dot{x}_1 = C_1e^{\lambda t}$, we have:

$$\ddot{x}_1 = C_1\lambda e^{\lambda t},\ x_1 = \frac{C_1e^{-2\xi\cdot t}}{-2\xi} + C_2$$

Substituting these into the Eqn. (5), we obtain: $\lambda = -2\xi$, thus the general solution of Eqn. (5) is written as:

$$x_1(t) = -\frac{C_1}{2\xi}e^{-2\xi\cdot t} + C_2 + \frac{F_0}{b_1}t \tag{6}$$

In which $\frac{F_0}{b_1}t$ is a particular solution, C_1, C_2 are integration constants, which are determined from the initial conditions. In our case, the initial conditions are: $x_1(0) = \dot{x}_1(0) = 0$, applying it into the Eqn. (6), we have:

$$C_1 = -\frac{F_0}{b_1}, C_2 = -\frac{F_0}{2\xi\cdot b_1}$$

Finally, substitution of these constants into the Eqn. (6) gives the general solution of Eqn. (3):

$$x_1(t) = \frac{F_0\cdot m_1}{b_1^{\ 2}}(e^{-\frac{b_1}{m_1}t} + \frac{b_1}{m_1}t - 1) \tag{7}$$

This is the expression of upper electrode displacement in the case of no reaction force from work piece.

For Eqn. (4) which is the representation for movement of lower electrode system, the initial conditions are:

$$t = 0,\ x_2 = -\frac{F_0}{k},\ \dot{x}_2 = 0,$$

Noting that the origin of coordinate x_2 takes the equilibrium position of mass m_2 under the action of gravity (m_2g).

If the coordinate is transformed to x'_2 which the origin is taken as the equilibrium position of mass m_2 under the action of force F_0 as shown in Fig.2, the Eqn. (4) will turn to be:

$$m_2\ddot{x}'_2+b_2\dot{x}'_2+kx'_2=F_0 \tag{8}$$

The solution is:

$$x'_2=\frac{F_0}{k_2}\left[1-\frac{e^{-\xi\cdot\omega\cdot t}}{\sqrt{1-\xi^2}}\cos(\omega_d\cdot t-\varphi)\right] \tag{9}$$

This is the expression of lower electrode displacement in the case of no reaction force from work piece.

Where: $\omega=\sqrt{\frac{k_2}{m_2}}$, $\xi=\frac{b_2}{2m_2\cdot\omega}$, $\omega_d=\omega\cdot\sqrt{1-\xi^2}$, $\varphi=\tan^{-1}(\frac{\xi}{\sqrt{1-\xi^2}})$.

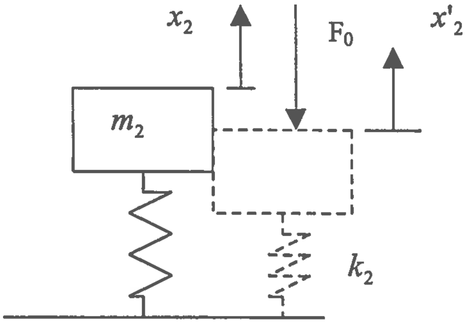


Fig. 2 Transform of coordinates

3. Breaking test

In order to determine the parameters required in the models above, a special test set-up is designed in such a way that it may be mounted directly between the electrode planes on traditional resistance welding machine as shown in Fig.3.

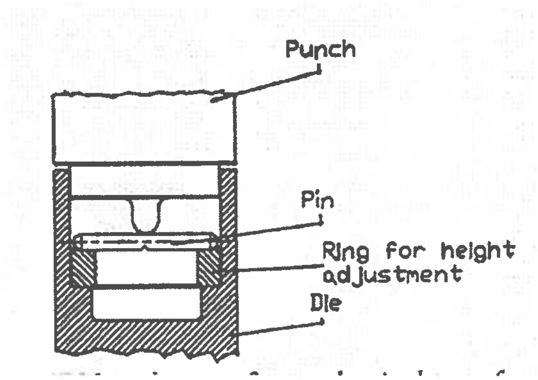


Fig.3 Breaking test set-up

A harden steel pin pressed by a punch mounted on the upper electrode breaks at a specific force (breaking force), simulating the momentary removal of load support. At this movement, the electrodes are separated temporarily, resulting in the upper electrode moving down rapidly under the acceleration of force F_0 and lower electrode bouncing back due to its stiffness, the movements are exactly the same as that described by the equations (3) and (4). By adjusting the diameter of the pins, different loads are applied. During the test, the load and the movements of both electrodes are measured simultaneously.

4. Determination of machine mechanical parameters

As mentioned above, the upper and lower electrode displacements x_1, x'_2 as well as the breaking force F_0 are measured in the breaking tests, therefore, the velocities $\dot{x}_1$, $\dot{x}'_2$ and accelerations $\ddot{x}_1$, $\ddot{x}'_2$ can be obtained by the numerical differentiation of displacements, i.e.

$$\dot{x}_N = (x_N - x_{N-1}) / \Delta t$$

$$\ddot{x}_N = (\dot{x}_N - \dot{x}_{N-1}) / \Delta t$$

Where, N is the number of points for each parameter. Applying these values to Eqn. (3), Eqn. (8) and rewriting it into the form of matrix, we have:

$$\begin{bmatrix} \ddot{x}_1(1) & \dot{x}_1(1) \\ \ddot{x}_1(2) & \dot{x}_1(1) \\ \cdots\cdots & \cdots\cdots \\ \ddot{x}_1(N) & \dot{x}_1(N) \end{bmatrix} \cdot \begin{Bmatrix} m_1 \\ b_1 \end{Bmatrix} = \begin{Bmatrix} F_0 \\ F_0 \\ \cdots \\ F_0 \end{Bmatrix}, \quad \text{that is:} \quad [A] \cdot \begin{Bmatrix} m_1 \\ b_1 \end{Bmatrix} = [F_0]$$

▼

$$\begin{bmatrix} \ddot{x}'_2(1) & \dot{x}'_2(1) & x'_2(1) \\ \ddot{x}'_2(2) & \dot{x}'_2(2) & x'_2(2) \\ \cdots & \cdots & \cdots \\ \ddot{x}'_2(N) & \dot{x}'_2(N) & x'_2(N) \end{bmatrix} \begin{Bmatrix} m_2 \\ b_2 \\ k_2 \end{Bmatrix} = \begin{Bmatrix} F_0 \\ F_0 \\ \cdots \\ F_0 \end{Bmatrix} \quad \text{that is:} \quad [A'] \cdot \begin{Bmatrix} m_2 \\ b_2 \\ k_2 \end{Bmatrix} = [F_0]$$

Therefore, the parameters m_1, b_1, m_2, b_2, k_2 are determined by conducting the computation based on least-squares method with software MATLAB:

$$\begin{Bmatrix} m_1 \\ b_1 \end{Bmatrix} = [A] \backslash [F], \quad \begin{Bmatrix} m_2 \\ b_2 \\ k_2 \end{Bmatrix} = [A'] \backslash\ [F_0]$$

5. Results of experiments and identification of mechanical parameters

As an example, Fig.4 shows the measured curves for a TECNA welding machine (250KVA) with the pneumatic press system. The curves in time range of AB corresponds to the duration of electrode separation after pin fractures (at breaking force of 3478N). Considering the electrode displacement is normally within 1mm and the lower electrode almost comes to still after bouncing back, only the beginning part of the curve for lower electrode displacement was used.

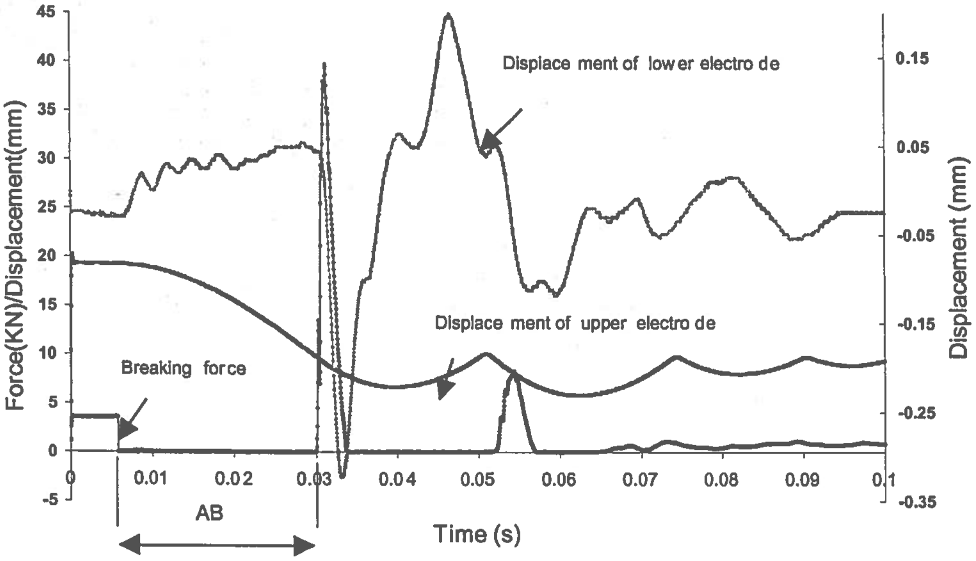


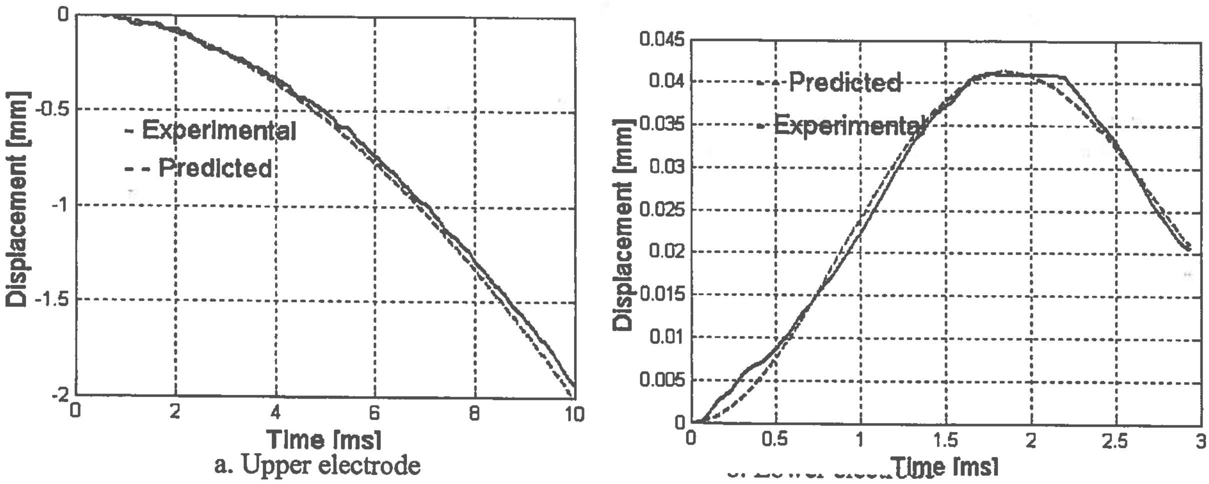
Fig.4 Measured curves at the breaking force 3478N for TECNA-250KVA machine.

Table 1 shows the determined values of mechanical parameters, in which the values of mass and stiffness are averaged and the damping coefficients are individually identified at different breaking forces.

Table 1. Determined mechanical parameters for TECNA-250KVA machine

Breaking force (KN)	**m_1** (Kg)	**b_1** (Kg/s)	**m_2** (Kg)	**b_2** (Kg/s)	**k_2** (N/m)
3.435	72.8	4004	52	32590	148783619
3.478	72.8	3926	52	14830	148783619
4.047	72.8	3775	52	33750	148783619
4.945	72.8	3518	52	25440	148783619
5.086	72.8	4891	52	45410	148783619
5.503	72.8	3521	52	43250	148783619
6.344	72.8	4355	52	48790	148783619
7.384	72.8	4163	52	50210	148783619
8.26	72.8	4226	52	42290	148783619
8.666	72.8	5034	52	49590	148783619
8.891	72.8	4212	52	37140	148783619
9.509	72.8	4506	52	51020	148783619
9.793	72.8	4750	52	58530	148783619
10.008	72.8	4488	52	47380	148783619

Applying the identified parameters into the mathematical models Eqn. (7) and Eqn.(9), very good agreements are achieved between the predicted and experimental results of the movements of electrodes, as shown in Fig.5.



a. Upper electrode

Fig. 5 Experimental and predicted results for TECNA-250KVA machine

6. Conclusions

The complex and coupled mechanical system of resistance welding machine is simplified as a lumped parameter system in which the basic parameters can be identified by using the experimentally measured force and displacements of electrodes. The test set-up used is suitable for different types of machine and the test can be performed in situ. By introducing a known reaction force into the model and the test set-up, the dynamic mechanical characteristics of machine in resistance welding process can be modeled and tested, which will be presented in the future.

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