Aspects on the study of nonlinear vibration phenomenon in friction welding with rotating active element

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Abstract. The friction welding with rotating active element is a complex process including heating of the materials using friction and plastic deformation generated by a tool that has both rotation and translation motions. The paper is analysing the nonlinear vibrations that occurs during the friction welding with rotating active element process, mainly due to the motion of the rotating element. Using the dynamic systems theory, the nonlinear equation of the motion is deduced and the motion characteristics are presented using specific qualitative methods. The results are contributing to a more accurate understanding of the phenomena, in this case the nonlinear vibrations, generated in the friction welding with rotating active element process, and to better performances of welding process.

1. Introduction

The idea of jointing two materials using friction emerged at the end of the 19-th century and is described by J. H. Bevington a patent, and used it to connect wires, edges and sleeves. The interest for this method continued in the XX-th century, the researches of Schaefer (1971), Meyer (1978) and Kes (1989) analysing the effects of the friction welding. However, the development of the technology was not at the standard required by the industry, at least in the first half of the century [1]. The soviet researchers also studied the method and developed an industrial technology for friction welding (a patent of A. I. Chudikov in 1956), later upgraded in SUA, Japan, UK and Germany. The result was a patent obtained by Caterpillar Tractor Co. in 1966, for “welding by inertial friction” [1].

Friction welding is now used by decades in industry for jointing and was initially known as “welding by rotation” and later, considering the linear welding, as “motion cinematic”, a pleonastic expression. Even nowadays, a lot of persons understand the “friction welding” through these two processes.

At present, other varieties of welding process are in place: orbital welding, circular welding for rectangular elements, rotational vibrations welding for round shaped elements (having high performance requirements) etc. The innovations in precision friction welding were focused on the operating technology for highly dynamic friction welding, precision measuring technology, friction welding technology in manufacturing, protection devices used in friction welding, control process in friction welding, real time communication of data in friction welding, increasing the productivity in friction welding by shortening the welding time etc. [2]. These areas of interest were covered by theoretical studies and experiments, both aiming to clarify and improve this technology. We are pointing out, only as examples, some researchers: De Backer & Bolmsjö [3], Gheorghiu & Bejinariu
Friction welding with rotating active element is a technology invented in 1991 at Cambridge, at the Institute for Welding Technologies [6]. This technology is allowing jointing two elements without melting the material, without pressing one to the other and without built-up material. The friction welding with rotating active element is a fast and inexpensive welding technology.

Friction welding with rotating active element is mainly used for the welding of aluminium and its alloys, due to the fact that the obtained joints are solid and with good plasticity. The welded elements are mainly flat and long (plates) but may be adapted for other thin profiles.

Friction welding with rotating active element is the result of combined friction heating and plastic deformation, using tool having both rotation and translation motions. The maximum temperature reached is 80% of the melting temperature. The diagram of the process is shown in figure 1 and the basic description of the process of friction welding with rotating active is the following. The active rotating element is having two parts: a massive part used to fix the tool in the machine and a slenderer, pointed part or “the pin” – the active part of the tool. After the proper positioning and fastening of the two work pieces to be welded, the active element is starting to rotate and to move toward the two pieces. The pin is penetrating the surface of the work pieces up to the massive part of the tool called “shoulder”. Due to the friction with the shoulder, the two work pieces are heated, obtaining a plastic area in the two work pieces to be welded. At this moment, the active rotating element is starting the translation motion on the welding line. As the active element moves, the heated material (by conduction) in the front of the pin is displaced in the gap behind the pin, generated by the translation of the pin. The shoulder of the active element is pressing down the welding, resulting a flat even weld seam. Any oxide film on the surface of the two pieces is dispersed due to the intense deformation. The process of local deformation is similar to a continuous extrusion process along the joint.

The section of the point may be a circle or a polygon, mainly a triangle or a square. The point may have a constant or variable section (i.e. a cylinder or a truncated cone) [4].

In the friction welding with rotating active element, the shape of the point, the rotation speed of the active element, the translation speed of the active element, the pressure applied by the active element, the characteristics of the welded materials are generating different configurations and mechanical characteristics of the bead of weld obtained.

![Figure 1. Schematic diagram – Friction welding with rotating active element](image1.png)

![Figure 2. The mechanical model used for the study](image2.png)

2. The model used for the study

The paper is developing an analytical study of the friction process generated by the translation motion of the active element. The approach is based on the nonlinear vibrations phenomena and is considering
only the qualitative aspects at this time. Accordingly, we adopted the model in figure 2, where \( M \) is the mass of the active element, \( k \) is the elastic coefficient of the active element, \( 2d \) is the width of the weld seam. The positions of the pin and the position of the elastic element are measured from \( O \) point.

The friction coefficients, \( \mu_1 \) and \( \mu_2 \) (considering the values in the plastic state of the workpieces) are not having the same value, so the friction force \( F_i \) generated between the tip and the work pieces is having different values and the differential motion equation may be written as follows [11], [12]:

\[
M \ddot{q} = \begin{cases} 
-F_{f_1}, & q \leq d; \dot{q} > u \\
-F_{f_2} - k(q - d), & q > d; \dot{q} > u \\
0, & q \leq d + \frac{F_{\mu_1}}{k}; \dot{q} = u \\
F_{f_1}, & q \leq d; \dot{q} < u \\
F_{f_2} - k(q - d), & q > d; \dot{q} < u 
\end{cases}
\] (1)

where \( u \) is the speed of the pin.

Integrating the motion equation (1) we obtain the following solution:

\[
q = \begin{cases} 
\frac{1}{2}R_i t^2 + C_1 t + C_2, & q \leq d; \dot{q} > u \\
C_i \sin(\omega t) + C_4 \cos(\omega t) + d - \frac{F_{f_2}}{k}, & q > d; \dot{q} > u \\
\frac{1}{2}R_i t^2 + C_1 t + C_2, & q \leq d; \dot{q} < u \\
C_i \sin(\omega t) + C_4 \cos(\omega t) + d + \frac{F_{f_2}}{k}, & q > d; \dot{q} < u 
\end{cases}
\] (2)

where \( R_i = \frac{F_{f_2}}{M} \), \( \omega^2 = \frac{k}{M} \) and \( C_i - C_4 \) are integration constants obtainable from the initial conditions:

\[
q = q_0 < d; \quad f_0 = \dot{q}_0 > u. \tag{3}
\]

If we are studying the phase plane trajectories from a qualitative point of view, we may use the variable \( f = \dot{q} \) in order to write the equations of the phase trajectories:

\[
f^2 = \begin{cases} 
-2R_i q + C_i^2 + 2R_i C_2, & f > u; q \leq d \\
\omega^2 \left[ C_i^2 + C_4^2 - \left( q - \left( d - \frac{F_{f_2}}{k} \right) \right)^2 \right], & f > u; q < a \\
\omega^2, & f > u; q < d + \frac{F_{\mu_1}}{k} \\
2R_i q + C_6^2 - 2R_i C_7, & f < u; q \leq d \\
\omega^2 \left[ C_6^2 + C_9^2 - \left( q - \left( d + \frac{F_{f_2}}{k} \right) \right)^2 \right], & f < u; q > a
\end{cases}
\] (4)
3. Results interpretation
The numeric simulation was performed using MATLAB, obtaining sets of graphics, representing the evolution in time of the solutions (2) and the associated phase plane trajectories (mainly parabola – see Table 1) using equation (4) and considering the condition (5). In figure 3 and figure 4 we are showing an example of a set of graphics, calculated considering \( k = 1 \text{ N/m}, F_f = 5 \text{ kN}, u = 3.927 \text{ m/s}, M = 250 \text{ kg} \) and \( d = 2 \text{ mm} \) [1], [2], [4].

![Figure 3. The time variation of the solutions (2)](image1)

![Figure 4. Phase plane trajectories](image2)

Because, for the moment, we want only to point out the conditions for a stable vibrational motion, we adjusted, as scale, some representative phase plane trajectories and overlapped them in order to obtain an overall, general qualitative image of the phenomenon (see figure 5).

\[
k < \frac{F_f^2}{Mf_0^2},
\]

(5)

![Figure 5. Phase plane \((q, \dot{q})\) trajectories – general qualitative](image3)

| No | Case | Description of the motion |
|----|------|---------------------------|
| 1. | \( f > f_0; q \leq d \) | Parabola intersects the straight line \( f = f_0 \) for \( q < d \) and the representative point is moving on this line up to point \( A \left( d + \frac{F_f^2}{k}, f_0 \right) \). |
| No | Case | Description of the motion |
|----|------|--------------------------|
| 2. | $f < f_0; q > d$ | For $k > \frac{F_{f_2}^2}{Mf_0^2}$, the representative point is moving on an ellipse, from A to $B\left(d, \sqrt{f_0^2 - \frac{F_{f_2}^2}{Mk}}\right)$, situated at the intersection with the straight line $q = d$. |
| 3. | $f < f_0; q \leq d$ | The motion is on a parabola up to point $C\left(d, \sqrt{f_0^2 - \frac{F_{f_2}^2}{Mk}}\right)$, for $k > \frac{F_{f_2}^2}{Mf_0^2}$. |
| 4. | $f < f_0; q > d$ | The representative point is moving on the same ellipse as in case 2, up to point A, then the motion is repeating periodically. |
| 5. | $f > f_0; q \leq d$ | Parabola intersects the line $q = d$ in $D(d, f_i)$, for $f_i > f$. |
| 6. | $f > f_0; q > d$ | Out of the initial conditions $q(0) = d; f(0) = f_1$, one may calculate the integration constants $C_C = \frac{f_1}{\omega}$ and $C_2 = \frac{F_{f_2}}{k}$. The representative point is moving on an ellipse from D until the phase trajectory is intersecting the straight line $f = f_0$, for $x < d + \frac{F_{f_2}}{k}$, then the representative point is moving on this straight line up to the point A. Afterwards the motion is similar to one in the case 1. |
| 7. | $f < f_0; q > d$ | Out of the initial conditions $q(0) = q_1; f(0) = f_0$, one may calculate the integration constants $C_1 = \frac{f_0}{\omega}$ and $C_2 = q_1 - \left(d + \frac{F_{f_2}}{k}\right)$. If the phase trajectory is intersecting the straight line $f = f_0$ in the point $E\left(q_0 = d - \frac{F_{f_2}}{k} + \sqrt{\frac{F_{f_2}^2 + M(f_1 - f_0^2)}{k}}, f_0\right)$, for $q_i \geq d + \frac{F_{f_2}}{k}$, the representative point is moving also on an ellipse, different from the one above, due to the different initial conditions. |
| 8. | $f < f_0; q > d$ | The motion on the ellipse in case 7 is possible until the phase trajectory is intersecting the straight line $q = d$ in the point $F\left(d, \sqrt{f_0^2 - \frac{F_{f_2}^2}{Mk}} + \sqrt{\frac{F_{f_2}^2}{Mk} + f_1^2 - f_0^2 - 2 \frac{F_{f_2}}{\sqrt{Mk}}}\right)$. |
| 9. | $f < f_0; q \leq d$ | The motion of the representative point is on a the parabola up to the intersection with the straight line $f = f_0$, then the motion is on this straight line up to the point A, then the motion is repeating like in the case 1. |

**Obs.:** For the initial conditions $q = q_0 < d; f = f_0 < u$, the representative point is moving first on the parabola $f < f_0; q \leq d$ and the study is reduced to the case 1. When the initial conditions are generating a dot in the marked domain in Figure 5, the motion of the representative point is going to be periodically from the beginning.
4. Conclusions
During the welding process, self-sustained vibrations are generated by the dry friction. These vibrations are nonlinear due to the friction force, as shown above.

The results interpretations (Table 1) are allowing us pointing out the characteristics of the solutions describing periodical motions, considering the weld seam width and the feed rate. This means that the possible pin trajectories may be identified, helping to better managing the technological process. Also, the more stable vibrations may be identified.

The less dangerous vibrations are the ones with the representative point moving on an ellipse or on a part of an ellipse: cases 2, 4, 7 and 8 from Table 1, because the motion is more predictable and a slight adjustment of the welding parameters may avoid any problem.

A possible problem may occur in the cases when the representative point is moving on a parabola or on a parabola and a straight line: cases 1, 3, 5, 6, 9, because the motion is less controllable and very small changes of the parameters may totally change the motion type. A special mention for the case 6, where the motion of the representative point is starting on an ellipse (meaning more stable motion) and then changing to the case 1.

The general qualitative results obtained are demonstrating that the study must go deeper in the quantitative aspects of the problem, in order to see which welding parameters or which constructive parameters may be better adjusted for a more stable motion.

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