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# Progressive wave: a new multisource vibration technique to assist forming processes - kinematic study, simulation results and design proposition

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## Abstract :

*Use of vibration in the forming process has already shown numerous advantages in the improvement of mechanical and surface properties of workpiece such as good surface or less friction between die and workpiece. The aim of this work is to develop a mathematical model of a progressive wave in the lower die due to the vibration given by multi piezoelectric actuators to assist the forging process. Based on the mathematical model, simulations using finite element software Forge2011® have been performed to observe the presence of progressive wave in the workpiece due to the movement of the lower die. The simulations' results confirm the existence of progressive wave in the workpiece and demonstrate the effect of progressive wave to reduce the forging load and improve the forging process.*

**Mots clefs :** Modeling, progressive wave, forging process

## 1 Introduction

The two traditional techniques to improve the forming process are using lubricants and preheating the material. The major benefits of using lubricants are reduction of forging load, tools' wear and improved surface finish (*surface effect*). The main limitation in using lubricants is the incompatibility with environment and its chemical reaction with tool/workpiece material. With the preheating method, the material's ductility increases while yield strength decreases (*volume effect*) but it affects important material properties such as surface structure, crystallographic structure and material strength as during heating there are voids, composition, and inclusion or precipitation formation. Application of vibration is the most recent and beneficial technique to improve the forming processes because it offers both surface and volume effects [1]. Moreover, it can prevent the undesirable effects related to two preceding techniques.

Until now, most of research in vibration assisted forming process concentrates on applying translational vibrations in axial and radial direction [2, 3, 4, 5, 6, 7, 8]. Some studies have been performed in the domain of orbital forging combined with translation [9, 10]. However, application of vibration in both translation and rotation to produce progressive wave during the forming process has never been discussed before. In this article, we will adopt this strategy to the metal forging process. The work will be presented in two parts. The first part is the kinematic study and mathematical modeling of progressive wave by using multi vibration sources. The second part concentrates on finite element simulations performed in software Forge2011® to see the impact of using progressive wave in the forging process and its affect on forging load's reduction. Finally, discussion on obtained results and perspective of experimental verification will be outlined in the last section of this paper.

## 2 Kinematic modeling of progressive wave on the lower die's movement

To establish a mathematical model of progressive wave on the lower die, the movement of two points in this die will be analyzed. Two Cartesian frames are used in this study:  $R_0$  is the one attached to the fixed base and  $R_d$  is the other attached to the lower die. In the  $R_d$  frame, a point M with coordinate  $(x, y, 0)$  and  $O_1$  with coordinate  $(x_1, y_1, 0)$  are considered for kinematic study (Figure 1). A cylindrical workpiece is put in contact with two die's surfaces and its symmetrical axis is on the  $O_z$  axis.

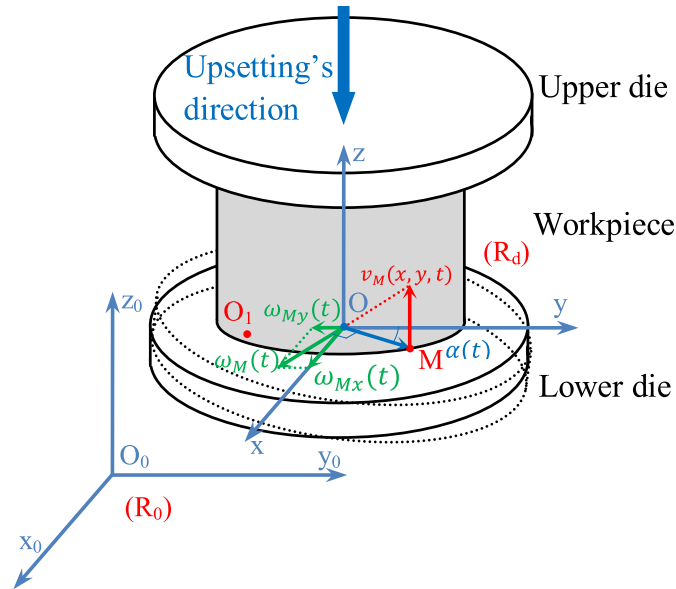


Figure 1: Kinematic scheme of the lower die in the forging process

If the movement of lower die is defined by two rotations (around x and y axes) and one translation (in z-direction). The rotation of the lower die expressed in the fixed base  $R_0$  can be presented by the following matrix:

$$R_x \cdot R_y = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & -\theta_x \\ 0 & \theta_x & 1 \end{bmatrix} \cdot \begin{bmatrix} 1 & 0 & \theta_y \\ 0 & 1 & 0 \\ -\theta_y & 0 & 1 \end{bmatrix} = \begin{bmatrix} 1 & 0 & \theta_y \\ \theta_x \theta_y & 1 & -\theta_x \\ -\theta_y & \theta_x & 1 \end{bmatrix} \quad (1)$$

with  $R_x, R_y$  are the matrix of rotation around x and y axes with the small angle of rotation  $\theta_x$  and  $\theta_y$ . The position of points M and O can be defined in  $R_0$ :

$$O_0 M_{(R_0)} = \begin{bmatrix} x \\ y \\ -x\theta_y + y\theta_x + z \end{bmatrix} \quad O_0 O_{1(R_0)} = \begin{bmatrix} x_1 \\ y_1 \\ -x_1\theta_y + y_1\theta_x + z \end{bmatrix} \quad (2)$$

Now, if the movement at point  $O_1$  is imposed as:

$$-x_1\theta_y + y_1\theta_x + z = z_a(t) \quad (3)$$

Then the movement of point M can be obtained as follows:

$$O_0 M_{(R_0)} = \begin{bmatrix} x \\ y \\ -(x - x_1)\theta_y + (y - y_1)\theta_x + z_a(t) \end{bmatrix} \quad (4)$$

If we assigned:  $x - x_1 = R\cos\psi$  and  $y - y_1 = R\sin\psi$ , then we can have:

$$z_M(t) = -R\cos\psi\theta_y + R\sin\psi\theta_x + z_a(t) \quad (5)$$

We are therefore capable of choosing a sinusoidal progressive wave for the cylinder of radius R and superposing a movement in z-direction defined by  $z_a(t)$ .

If we are only interested in the generation of progressive wave, then  $\Delta z(t) = -R\cos\psi\theta_y + R\sin\psi\theta_x$  depends only to the radius R of workpiece and the amplitudes of rotation angles. In the case of having an error in workpiece's centering in the lower die, a movement in z-direction is imposed on the workpiece in such way  $z(t) = R_1\cos\psi_1\theta_y - R_1\sin\psi_1\theta_x$  with maximum amplitude  $R_1\theta_{max}$ .

In the other hand, if we want to achieve the sufficient amplitude at one point on the die to keep the workpiece on the die and to obtain the maximum velocity of deformation  $V_0$ , it is only important to consider the velocity at point M on the die. The lower die's radius determines the amplitudes of the movement around rotations' axes and the movement along z.

In this paper, only the progressive wave created by two rotations around two axes  $O_x$  and  $O_y$  will be studied. Consider the movement of a point M at the lower surface of the workpiece in a distance R from the center O. At time t, the position of point M in the coordinate  $O_{xy}$  is defined by an angle  $\alpha$  between  $O_x$  and OM.

The tangential velocity at point M is defined by  $\vec{v}_M$  and is calculated as:

$$\vec{v}_M(x, y, t) = \vec{\omega}_M(t) \times \vec{OM} \quad (6)$$

The constant angular velocity vector  $\vec{\omega}_M$  is projected on the two axis  $O_x$  and  $O_y$  and is given by :

$$\begin{aligned} \omega_{Mx}(t) &= \Omega_0 \cos \alpha \\ \omega_{My}(t) &= \Omega_0 \sin \alpha \end{aligned} \quad (7)$$

with  $\Omega_0$  is the maximum amplitude of angular velocity and  $\alpha = \omega t$ , where  $\omega$  is the angular velocity of vector  $\vec{\omega}_M$  around  $O_z$ .

The angular displacement  $\theta_x$  and  $\theta_y$  can be calculated by the following equations:

$$\begin{aligned} \theta_x(t) &= \int_0^t \omega_{Mx}(t) dt = \theta_{x_0} + \frac{\Omega_0}{\omega} \sin(\omega t) \\ \theta_y(t) &= \int_0^t \omega_{My}(t) dt = \theta_{y_0} - \frac{\Omega_0}{\omega} \cos(\omega t) \end{aligned} \quad (8)$$

where  $\theta_{x_0}$  and  $\theta_{y_0}$  are the initial angles of rotation.

The upper die is supposed to move down at a constant velocity  $V_0$ . The instantaneous height reduction due to these dies' movement can be written as follows:

$$h(t) = h_0 - V_0 t - R\theta(t) = h_0 - V_0 t - R \int_0^t \Omega_0 \sin(\omega t + \phi) dt \quad (9)$$

where  $h_0$  is the initial height of workpiece and  $\theta(t) = \int_0^t \Omega_0 \sin(\omega t + \phi) dt$  is the angle de rotation due to the angular velocity vector  $\vec{\omega}_M$  at the point M at the moment t with the initial angle  $\phi$ .

Height reduction rate at point M can be written:

$$\dot{h}(t) = -V_0 - R\Omega_0 \sin(\omega t + \phi) \quad (10)$$

From equation (10), we can obtain  $\dot{h}_{max} = -V_0 + R\Omega_0$ . If  $\dot{h}_{max} > 0$ , the contact between the workpiece and dies is lost, therefore, the maximum value of  $\dot{h}_{max}$  is 0. In that case, the maximum amplitude of the rotation depends on the defined velocity  $V_0$  and the radius of the workpiece:

$$\Omega_{0max} = \frac{V_0}{R} \quad (11)$$

### 3 Finite element simulation for forging process with multisource vibrations

Finite element simulations have been performed in viscoplastic domain for forging processes with and without vibrations in FORGE2011<sup>®</sup>. Since this paper focuses on a viscoplastic material, the material behavior can be expressed by Norton-Hoff constitutive law (extracted from Hansel and Spittel rheology law), according to which:

$$\sigma_0 = k \dot{\varepsilon}^n \varepsilon^m \quad (12)$$

From the equation (12), it can be seen that the flow stress  $\sigma_0$  depends on the equivalent deformation  $\varepsilon$ , the equivalent deformation rate  $\dot{\varepsilon}$  along with the coefficients of material (the consistency  $k$ , the hardening coefficient  $n$  and the sensitivity to strain rate  $m$ ). Because this study is about cold forging process, the temperature terms are not included in this model. Friction is taken into account by using a Coulomb limited Tresca model in this case.

The input data for this simulation is the two angular velocities generated by the equations (7) and transferred to software FORGE2011<sup>®</sup> with the help of generic press for further use during the forging process. Figure 2 presents the FORGE model, showing the three main parts of the forging process (upper die, workpiece and lower die). Table 1 summarizes the different parameters of model and process used in these simulations.

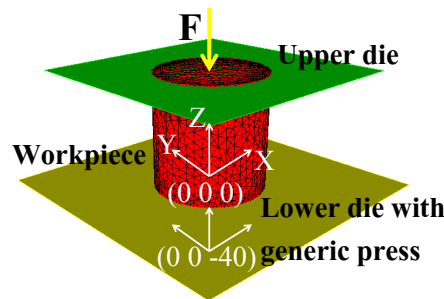


Figure 2: FORGE2011<sup>®</sup> model for FEM simulations

Table 1: FEM model parameters used forging process simulations

| Parameters                                | Values  |
|---|---|
| Workpiece material coefficient (Aluminum) | $K = 161.9; n = 0.2; m = 0.1$                   |
| Friction coefficients                     | $\mu = 0.05, m = 0.8$                           |
| Workpiece geometry                        | $R = 20\text{mm}; h_0 = 40\text{mm}$            |
| Workpiece final height                    | $h_f = 15\text{mm}$                             |
| Upper die velocity                        | $V_0 = -3\text{mm/s}$                           |
| Progressive wave frequency                | $f = 10\text{Hz}$                               |
| Rotation velocity                         | $\Omega_0 = \Omega_{0max} = 0.15\text{rad/sec}$ |

The simulation starts at time  $t=0$ , then the initial angular displacements  $\theta_{x0}, \theta_{y0}$  are calculated from the equation (8) as follows:

$$\begin{aligned} \theta_x(0) &= 0; & \theta_y(0) &= 0; \\ \Rightarrow \theta_{x0} &= 0; & \theta_{y0} &= \frac{\Omega_0}{2\pi f} = \frac{V_0}{2\pi f R} = -0.00239\text{rad} = -0.137^\circ \end{aligned}$$

Presence of rotation in the lower die can be found out by measuring displacement for small period of time. Similarly, the presence of rotation on the lower surface of workpiece can be measured with the help of a-priori sensors. These sensors can also be used to find out other important data measurement such as total strain, strain rate, displacement and velocities in x, y and z directions.

Once the presence of rotation at the upper surface of lower die and in the lower surface of workpiece has been verified, the effect of the multi vibration on the forging process can be observed. This can be done by comparing the forging load required for the processes with and without multi vibration.

This comparison has been presented in Figure 3. Figure 3(a) presents load required for the forging processes with and without vibration. It shows that there is forging load reduction when multi vibrations have been applied.

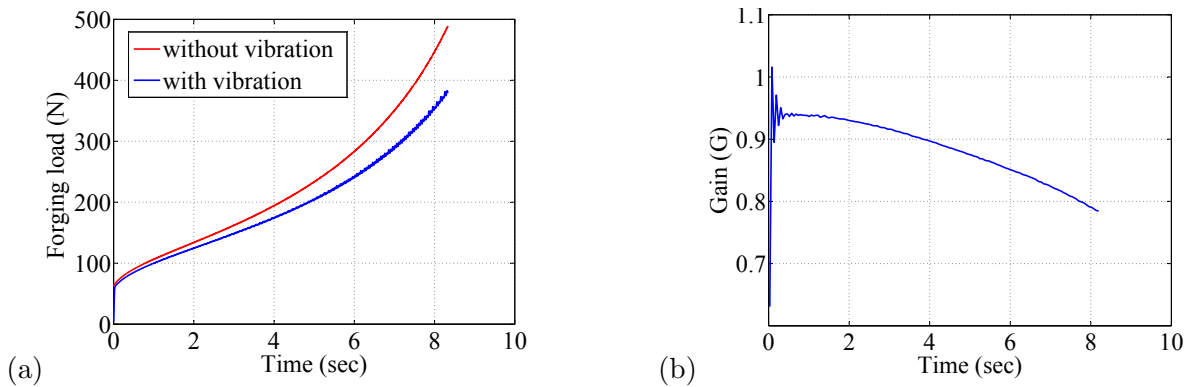


Figure 3: (a) Load versus time for forging processes with and without multi vibration (b) Gain in forging load reduction :  $f=10\text{Hz}$  and  $\Omega_{0max} = 0.15\text{rad/sec}$ .

Normalized load reduction can be found out by normalizing the forging load over the time. Normalized load reduction or gain in forging load reduction is presented in Figure 3b. Forging load reduction of 21.5% has been obtained at the end of the process. It can be seen that initially gain in forging load reduction is small but with time, this gain has increased as plastic deformation increases. This phenomenon shows the advantage of using progressive wave in the forging process.

On Figure 4, the velocity field has been plotted for two time instants during the time period  $T = 0.1\text{s}$  ( $t=2-2.1\text{s}$ ). It can be clearly seen that there is change in the velocity vector's direction from the right side of workpiece in the figure 4(a) to the left side of workpiece in the figure 4(b) during a half period of the progressive wave. This explains the reduction of the stress in the material and the reduction of the friction on the lower die.

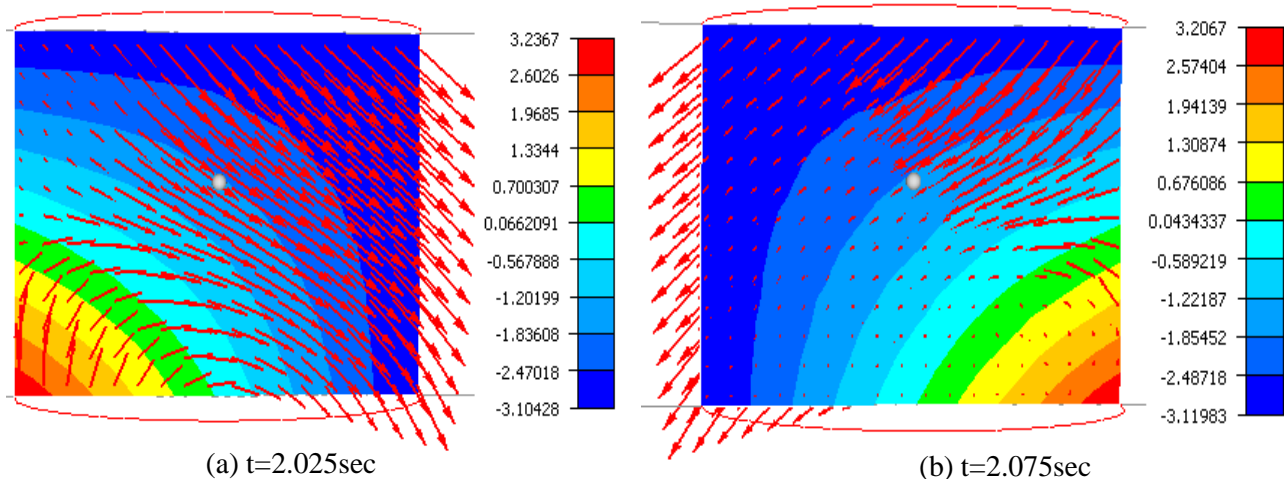


Figure 4: Velocity field of workpiece (a)  $t = \frac{T}{4}$  (b)  $t = \frac{3T}{4}$

## 4 Conclusions and future work

In this work, generation of progressive wave is predicted with the help of multiple vibration sources during the forging process. The kinematic study has been presented and applied during the forging process simulation performed in the Forge2011®. Simulation's results confirm the gain in forging load reduction. Idea of applying multi-vibration sources to generate progressive wave during the forging process has been discussed for the first time and an experimental approach to employ it is needed.

In the future work, a comparison with experimental reduction in forging processes is needed to confirm these simulation results. A mechanical system must be designed with the strict conditions to support the forging load (up to 10 kN) and generate the displacements (in order of  $\mu\text{m}$ ) to perform a proposed progressive wave of movement in the lower die. A kinematic scheme of mechanical system is presented in Fig. 5. However, the use of elastic guiding in place of the conventional guiding must be considered to prevent the mechanical backlash which is incompatible with the very small required displacements.

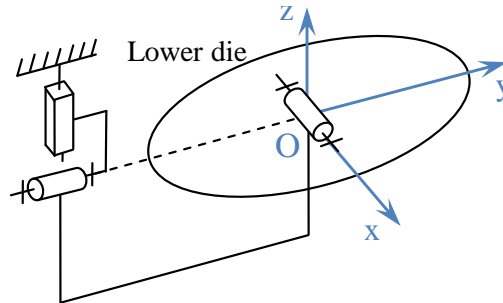


Figure 5: Kinematic scheme of mechanical system

The piezoelectric actuators, which are widely used for this kind of application [2], are promising sources of vibrations to meet these requirements. However, a methodology for designing and controlling mechanical system integrating multi piezoelectric actuators must be studied further to realize the proposed kinematic movement.

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