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Effects of Vibrations on Metal Forming Process: Analytical Approach and Finite Element Simulations

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Abstract. Vibration assisted forming is one of the most recent and beneficial technique used to improve forming process. Effects of vibration on metal forming processes can be attributed to two causes. First, the volume effect links lowering of yield stress with the influence of vibration on the dislocation movement. Second, the surface effect explains lowering of the effective coefficient of friction by periodic reduction contact area. This work is related to vibration assisted forming process in viscoplastic domain. Impact of change in vibration waveform has been analyzed. For this purpose, two analytical models have been developed for two different types of vibration waveforms (sinusoidal and triangular). These models were developed on the basis of Slice method that is used to find out the required forming force for the process. Final relationships show that application of triangular waveform in forming process is more beneficial as compare to sinusoidal vibrations in terms of reduced forming force. Finite Element Method (FEM) based simulations were performed using Forge2008® and these confirmed the results of analytical models. The ratio of vibration speed to upper die speed is a critical factor in the reduction of the forming force.

Keywords: Vibrations assisted forming; visco-plastic domain; analytical model; finite element method (FEM)

INTRODUCTION

Application of vibration during the forming process have been found useful in the recent years. First application of vibration during the forming process was performed in 1953 [1] and since then, many laboratories started using vibration during the plastic forming. Up to now, most of the work done is related to vibration assisted forging, extrusion and wire drawing process. During the research in vibration assisted extrusion process [2], it has been found that if extrusion speed is kept below certain critical speed, then by use of ultrasonic vibrations, extrusion force and material flow stresses can be reduced. The average extrusion force can also be decreased by reducing the extrusion speed or increasing the amplitude of vibration.

Application of ultrasonic-vibration on the dies of tube and wire drawing also reveals reduction of the forming forces, flow stress, friction between die and work-piece, production of better surface qualities and higher precision. Study shows that the extent to which an oscillation may be advantageous depends upon the speed of processing, the type of process, the lubricant used, the mode of oscillation and the material being used [3] and [4].

The study of upsetting a model paste with ultrasonic vibration presents consistent result of compression tests when ultrasonic vibration is superimposed on the static load. During the intervals of superimposed vibration, constant die vibration amplitude of $10\mu\text{m}$ and frequency of 20kHz were maintained. Applying ultrasonic oscillation results in an immediate drop in the mean forming load [5]. Majority of the work done in analyzing the effect of vibration on forming process is in the range of ultrasonic but the industrial application of ultrasonic vibration is limited by the power rating of ultrasonic generators and low frequencies are usually recommended. Forging with a superimposed vibrational load at 10-40Hz frequency gives a 50 percent increase in deformation and a similar reduction in specific pressure. The tendency of the blank forged to assume a barrel-like shape is also reduced, as a result of which both the stresses and the strains are more uniformly distributed [6].

Researchers have also investigated the upsetting of plasticine [7] and performed the FEM analysis. They prove that if deformation is performed under superimposed vibration, the mean stress necessary to maintain plastic flow decreases in comparison to purely static deformation. According to their study, amplitude has more impact as compare to frequency for mean forming force reduction and also finite element simulations can accurately predict the effects of a superimposed oscillation load on the forming force in upsetting of a elastic-viscoplastic material.

In this work, first, analytical models for vibration assisted forging process will be presented. These models are based on Slice method that will be used for finding out gain in forging force reduction for two vibration waveforms i.e. sinusoidal and triangular. In the second part, the finite element method based simulations for vibration assisted forging process will be presented. Finally, in the third part, the study will be extended to the elasto-viscoplastic domain for vibration assisted forging and extrusion process.

ANALYTICAL MODEL FOR FORGING PROCESS

Slice/Slab Method

In this paper, the classical method known as Slice/slab Method is used for prediction of forging force. This method is used for both forging processes with and without vibrations. This method is easy to apply and is quite simple but capture the influence of friction between the workpiece and die. This method is based on following assumptions:

- Shape of the workpiece will remain same throughout i.e. cylinder remains cylinder and parallelepiped remains parallelepiped
- No thermal effect will be considered
- Only applicable to viscoplastic domain

The work piece used in this study is cylindrical in shape and forging force required to reduce its height is given by Slice method:

$$F = \frac{\pi D^2 \sigma_0}{2A} \left[\frac{1}{A} (e^A - 1) - 1 \right] \quad (1)$$

Here D is diameter of workpiece, $A = \frac{\bar{m}D}{h}$ where \bar{m} is Tresca friction coefficient and h is the height of the workpiece. The flow stress σ_0 can be obtained by Norton-Hoff law with $\sigma_0 = k \varepsilon^n \dot{\varepsilon}^m$, k is consistency of material, n and m are material coefficients. Forging force can be rewritten in terms of function of height $\Phi(h(t))$, which is itself changing with time :

$$F(t) = \Phi(h(t)) \varepsilon^n(t) \dot{\varepsilon}^m(t) \quad (2)$$

Change in the height of the workpiece with respect to time is $h(t) = h_0 + v_0 t + v_1(t)$ and $\dot{h}(t) = v_0 + \dot{v}_1(t)$ where h_0 is the initial height of workpiece, v_0 is mean velocity of die and $v_1(t)$ is vibration velocity. Deformation in the direction of reduction of cylinder's height is given by:

$$\varepsilon(t) = \frac{h_0}{h(t)} - 1 \quad (3)$$

Deformation rate is given by:

$$\dot{\varepsilon}(t) = -\frac{h_0 \dot{h}(t)}{h^2(t)} \quad (4)$$

If there is no vibration: $v_1 = 0$ then from Eq. 2, the final expression of the forging force without vibration is given by:

$$F_0 = \Phi(h(t)) \left[\frac{h_0}{h(t)} - 1 \right]^n \left[-\frac{h_0 v_0}{h^2(t)} \right]^m \quad (5)$$

Sinusoidal Vibrations

If sinusoidal vibrations are applied then $v_1(t) = v_1 \cos(2\pi f t)$ with amplitude $a = \frac{v_1}{2\pi f}$ and angular velocity $\omega = 2\pi f$, where f is frequency in Hz. For sinusoidal vibrations, the forging force can be found as

$$F_s = \Phi(h(t)) \left[\frac{h_0}{h(t)} - 1 \right]^n \left[-\frac{h_0(v_0 + v_1 \cos(2\pi f t))}{h^2(t)} \right]^m \quad (6)$$

It is supposed that the function $\Phi(h(t))$ depends weekly on the sinusoidal vibration. Then the ratio $G = F_s/F_0$ is given by:

$$G(t) = \left[\frac{v_0 + v_1 \cos(2\pi ft)}{v_0} \right]^m = [1 + R \cos(\omega t)]^m \quad (7)$$

This equation represents the gain in forging force reduction with $R = \frac{v_1}{v_0}$ is the speed ratio. In a particular case of $R = 1$, final solution obtained is¹:

$$\bar{G} = -\frac{2^m \Gamma(m+0.5)}{\sqrt{\pi} \Gamma(m+1)} \quad (8)$$

This equation shows that gain in forging force reduction is only function of sensitivity of strain rate (m) keeping speed ratio R constant. The curve representing this equation is plotted in Fig. 5.

Triangular vibration

Triangular waveform can also be applied in place of sinusoidal. All the equation derived before are valid with some modification for the velocity term (v_1) with vibration. For triangular vibration, two velocity terms v_1^+ and v_1^- are present defining wave (signal) going up velocity and velocity going down velocity as can be seen from Fig. 1. Here, α represents the duty ratio, that is the indication of signal up and down time. Mean speed can be written as:

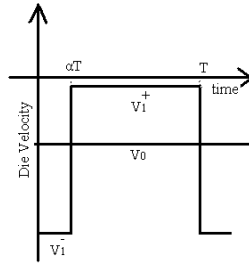


FIGURE 1. Velocity profile for triangular waveform

$$v_0 = \frac{1}{T} \int_T v(t) dt = \alpha v_1^- + (1 - \alpha) v_1^+ \quad (9)$$

The amplitude of square wave is $A = v_1^+ - v_1^-$, then v_0 will be:

$$v_0 = \frac{1}{T} \int_T v(t) dt = v_1^- + (1 - \alpha) A \quad (10)$$

One particular case is considered here i.e. $v_1^+ = 0$, then $v_1^- = -A$ and Eq. 10 will become

$$v_0 = -\alpha A \quad (11)$$

For triangular waveform, overall gain in forging force reduction is given by following equation:

$$\begin{aligned} \bar{G} &= \frac{1}{T} \int_0^T (G(t)) dt = \frac{1}{T} \int_0^T \left(\frac{v_1(t)}{v_o} \right)^m dt \\ &= \frac{1}{T} \int_0^{\alpha T} \left(\frac{v_1^+}{v_o} \right)^m dt + \frac{1}{T} \int_{\alpha T}^T \left(\frac{v_1^-}{v_o} \right)^m dt \end{aligned} \quad (12)$$

¹ The math function $\Gamma(x)$ is defined by $\int_0^\infty t^{x-1} e^{-t} dt$

$$= \left(\frac{v_1^+}{v_0} \right)^m \alpha + \left(\frac{v_1^-}{v_0} \right)^m (1 - \alpha) \quad (13)$$

Putting the values of v_0 from Eq. 11, the following analytical solution can be obtained:

$$\bar{G} = \alpha^{1-m} \quad (14)$$

This equation shows that gain depends on m (sensitivity of strain rate) if duty ratio is kept constant. Curve for analytical solution of triangular vibrations is shown in Fig (5).

FINITE ELEMENT SIMULATIONS OF FORGING PROCESS WITH VIBRATION

Viscoplastic Domain

In this section, finite element based software Forge2008® simulations are investigated for forging process. The vibrations are included in the simulations through the routine running behind the simulations. The aim of these simulations is to validate the proposed analytical models. In order to evaluate the influence of the kinematic assumption used to elaborate the model, a purely viscoplastic material is considered, both in the case of sinusoidal and triangular vibration waveforms. The parameters of Norton-Hoff, consistency K and hardening coefficient n of the material were kept constant, while the sensitivity of strain rate m was varied in the range of 0.1 to 0.9 to compare it with the analytical model. Thermal effects were canceled and the friction is modeled using a tresca model with $\bar{m} = 0.8$. Table 1 summarizes the different parameters used in these simulations.

TABLE 1. FEM Model parameters used for simulations.

Workpiece material	$K = 161.9, n = 0.2$ $0.1 \leq m \leq 0.9$	Simulation model	Axisymmetric
Tresca friction coefficient	$\bar{m} = 0.8$	FEM software	FORGE 2008®
Workpiece diameter	40mm	Die	Non deformable (Rigid)
Workpiece initial height	40mm	Workpiece Meshing	Triangular
Workpiece final height	15mm	Time step (with vibrations)	0.25 ms (fixed)
		Time step (without vibration)	25 ms (fixed)

Fig. 2 shows the model geometry in Forge2008®, where the sinusoidal or the triangular vibration is simulated by the appropriate expression for term v_1 using a Fortran routine. For all simulations, the upper die speed is constant, $v_0 = 3 \text{ mm.s}^{-1}$. In the case of sinusoidal vibration, the amplitude a is chosen such that $a\omega = v_0$. Here the trade off was

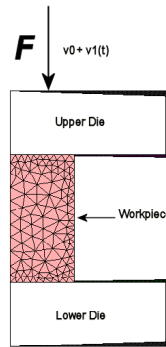


FIGURE 2. Forging model for upsetting in FORGE 2008 with vibration application

imposed by the software, since enough step per period must be simulated. The choice was to use a frequency $f = 40$ Hz, and $a = 12 \mu\text{m}$. Setting a fixed step of 0.25 ms ensures that 100 points per period will be available. The Fig. 3(a) clearly shows the expected effect of forging force reduction with the application of vibrations. In the case of triangular waveform, the waveform is chosen such that the mean speed is 3 mm.s^{-1} , and $v^+ = 0$. For this purpose, amplitude is calculated that corresponds to frequency 40Hz and duty ratio 0.1. The calculated value of amplitude is found to be $a = 67.5 \mu\text{m}$. Fig. 3 (b) presents the curves for forging force versus time for triangular waveform.

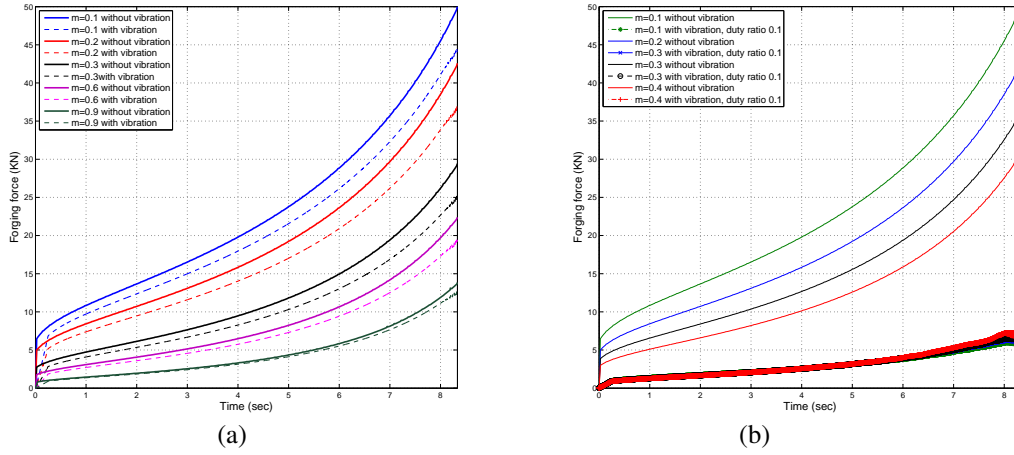


FIGURE 3. Effect of m on the forging process: (a) with sinusoidal vibration $v = 3 \text{ mm/s}$, $f = 40 \text{ Hz}$ and $a = 12 \mu\text{m}$, (b) with triangular vibration $v = 3 \text{ mm/s}$, $f = 40 \text{ Hz}$ and $a = 67.6 \mu\text{m}$

Elasto-viscoplastic domain

In the context of industrial processes, it is more realistic to consider the elastic behavior as well. It can be expected that the previous results will not apply and that elasticity can mitigate the benefit of vibration. Hence, in this section, without the guidance of a model, the influence of change of different process parameters is studied through simulation. Frequencies and amplitudes will be considered to improve forging process. Table 2 presents data that sum up the parameters used in these simulations. Material and friction coefficients are also mentioned and are kept constant throughout these simulations. The study is limited to sinusoidal vibrations and material used is Aluminium 99.

TABLE 2. Parameters data for forging process

Frequencies	$f = 40\text{Hz}, 60\text{Hz}, 80\text{Hz}$	Strain rate sensibility	$m = 0.3$
Amplitudes	$a = 12\mu\text{m}, 18\mu\text{m}, 24\mu\text{m}$	Hardening sensibility	$n = 0.2$
Die velocities	$v_0 = 3\text{mm/s}$	Friction data	$\mu = 0.05, \bar{m} = 0.1$
Material consistency	$k = 161.9$		

Fig. 4(a) and (b) presents the reduction ratio of the forging force obtained for the simulations when the frequency and amplitude are varied. All the curves are calculated after filtering the vibrations (using the same filter over 10 periods), and normalising them against the forging force without vibration. Filtering introduces some transient that are noticeable at the beginning and the end of the curves.

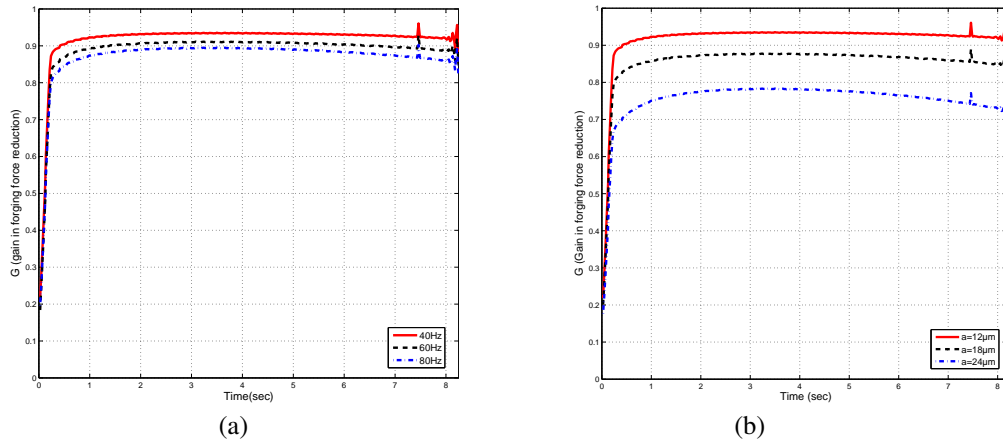


FIGURE 4. Forging force reduction ratio : (a) for different frequencies at ($v = 3 \text{ mm/s}$, $a = 12\mu\text{m}$), (b) for different amplitude at ($f = 40 \text{ Hz}$, $v = 3 \text{ mm/s}$)

RESULTS AND DISCUSSION

Fig. 5 sums up the results of analytical and simulated gain in force reduction for sinusoidal and triangular waveforms. It can be seen that the correlation between the analytical and simulation models are excellent especially for triangular waveform. In the case of sinusoidal waveform, the simulated results are better than expected. Simulations including temperature and varying the Tresca coefficient were also performed but they are not presented here as no noticeable impact has been found on the results.

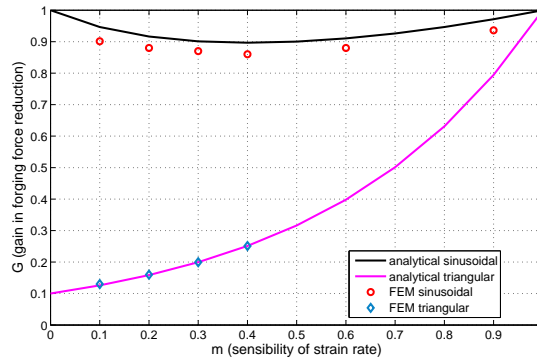


FIGURE 5. Comparison of analytical models and FE simulations in viscoplastic domain for vibration assisted forging process

The speed ratios corresponding to the frequencies and amplitudes used in Fig.4(a) and (b) are all greater than one ensuring that partial elastic unloading is obtained. The results are worth noticing that there is a reduction in the forging force: as the frequency and amplitude increase (speed ratio increases), the forging force reduces. There would also have been an impact of the friction and temperature however, these hypothesis are still to be investigated.

CONCLUSIONS AND PERSPECTIVE

In this paper, two analytical models have been proposed in the viscoplastic domain. These models are based on a slice model combined with a Norton-Hoff law. The insight provided by the analytical models was used to identify two important factors, first the speed ratio (the ratio of the die constant speed v_0 and vibration speed v_1) and the second is the duty ratio (α). Owing to the FEM simulations, the predicted reduction of the forging force has been validated. Based on these models, a triangular waveform has been proposed, that can improve further the benefits of using vibrations. The FEM have been then exploited to explore the potential benefits in the elasto-viscoplastic domain. It was found that vibrations also have a beneficial impact and that the same factor (speed ratio) is relevant. In future works, the analytical model will be extended to direct extrusion.

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