Investigation of the Axial Forming Force during Low Frequency Vibration Assisted SPIF.

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Abstract Applied low frequency vibration in a single point incremental forming technique has recently been used. Through process of the Single-Point Incremental Forming (SPIF), the precision was affected by forming force and can cause sheet metal fracture. The magnitude of the forming forces is necessary for designing suitable models for the metal forming of the Incremental Layer. Using vibration with various values of frequency (20, 40, 60, 80, 100) Hz with amplitude (0.1mm) can decrease the forming force. It is established that the reduction rate in axial force is about (11.63%) at the frequency of (100 Hz), it is the lowest for the selection of frequencies introduced. The experimental force result has been compared with analytical solution

Keywords: SPIF, Axial forming force, Low frequency vibration

1. Introduction

The single-point incremental forming process (SPIF) is an excellent adaptability, due to the fact that by the same die and the same punch, in accordance with the movements that levied to the energetic elements and the use of the similar machine tool, numerous unique forms can be achieved. The forming force was analyzed and calculated according to that the parameters of the sheet metal parts forming changed with vibration [1]. Depending on the results using experimental and numerical simulation, the tool rotational speed affected on the friction coefficient, forming force and forming precision [2]. The forming force has been measured in Single-Point Incremental Forming and Two-Point Incremental Forming of sheet metal. It's known that the force value is necessary when attempting to locate when equipment is able to form the sheet metal. The forming forces value is required to develop suitable models for the incremental sheet forming [3]. The influence of parameters (tool rotating, spindle speed and feed rate) on the forming force and surface quality were studied [4]. In the investigation of an experimental method able to measure the forming forces during an incremental forming process and utilizing a table-type force dynamometer with an incremental sheet metal forming rig, the (3) force components during the process of forming were measured [5]. Applying Low frequency vibration during the incremental forming process may reduce the forming force and smooth the grain structure. Recently, the incremental sheet metal method with low frequency vibration has become a reliable technology [6]. The objective from this work is adding vibration with range of frequency (20, 40, 60, 80 and 100) Hz to the forming process and study its effect on axial forming force. The other parameter like (Tool rotating, Spindle speed, and Feed rate) will be constant.
2. Used Equipment

As depicted below, the experimental system facilities are:

1) A 3-axis CNC vertical milling machine, as shown in figure (1)
2) A system of vibration composing of exciter motor as well as speed control.
3) Load cell connected to HX711 Load Cell Amplifier. The sensor used in this experiment was S type load cell. The forming force in the Z directions was recorded throughout the experiments.
4) Control box chiefly comprises Arduino to interface with computer, board of sensor connection, and motor driver.
5) Sheet metal fixture utilized for fixing the sheet.
6) Power Supply used for converting the (AC) to (DC) current and governing the resulted voltage.
7) Computer.

Figure (2) manifests the cone shape that was formed via single-point incremental forming process. The cone shape dimensions and the machine parameters are illustrated in Table (1).

![Figure 1. 3-axis CNC vertical milling machine](image1)

![Figure 2. Simple cone shape](image2)

| Tool diameter | Feed rate | Speed rotate | Vertical step size | Cone diameter | Wall angle | Depth |
|---------------|-----------|--------------|-------------------|---------------|------------|-------|
| 12 mm         | 400 mm/min| 200 rpm      | 0.25              | 100 mm        | 45°        | 30 mm |

For the forming study, the alloy Al-1050 with 1 mm thickness was used and its mechanical properties being outlined in Table (2). The sheet metal has a dimension of (300 × 400) millimeters clamped into a fixture with a backing plate containing an orifice of 105 mm that will form the cone within. To investigate the effects of vibration on the SPIF, the practical evaluations were carried out with and without vibrations. The product shape of the forming process was a truncated simple cone for the convenience of subsequent measurements.
Table 2. Mechanical properties of the used alloy Al-1050

| Property                  | Value          |
|---------------------------|----------------|
| Density $\rho$ (kg/m$^3$) | $2700$ kg/m$^3$|
| Young’s Modulus $E$ (GPa) | $75$ GPa       |
| Poisson’s Ratio $\nu$     | $0.33$         |
| Yield Stress $\sigma_y$   | $78$ MPa       |
| Tangent Modules $E_t$     | $0.2$ GPa      |

3. Analytical Model of the Forming Force for SPIF

A new analytical model has been developed for the vertical forming force. The area of contact between the forming tool and the sheet metal was initially assessed, and the effective stress was then calculated. To predict the vertical force of forming in the sheet metal forming process, the area of contact is very important, figure (3). The contact area can be split into three parts [7]:

1. The contact part formed via the pressure of tool, named $l_1$.
2. The contact portion where the tool formed the wall angle, pointed $l_2$.
3. The contact section between surface scallop and tool, stated as $l_3$.

![Figure 3. Meridional part of the contact area](image)

The thorough contact portion between the tool of forming and the metallic sheet is manifested in figure 4. The tool pressure causes the section $l_1$ which is denoted by the quantity pressed, and $h_1$ is the height of non-deformed plate that flows by the tool within the tool bottom, and $h_1$ is to be the same but does not equal to the depth of step. Also, $h_1$ is split into the thinning of sheet thickness ($h_1'$) and the elastic deflection ($h_1''$) in the perpendicular direction.

![Figure 4. Geometric graphic of the sheet thickness beneath the head of tool](image)
\[ h_1' \approx [1 - \frac{\alpha}{\alpha + \arccos\frac{r-h_1'}{r}} \cdot t(1 - \cos\alpha + t \cos\alpha)] \] (1)

For simplifying the computation, the Taylor formula might express an inverse cosine function. One can rewrite Eq. (1) in the form of

\[ h_1' = t(1-\cos\alpha) \cdot \frac{\pi}{2} \cdot \frac{r-h_1'}{r} \] (2)

Because \( h_1' \) being smaller than the radius of tool (r), one can cancel the part \( h_1'/r \), and obtain Eq. (2) in the form of

\[ h_1' = \frac{t(1-\cos\alpha)}{\alpha(3-\frac{\pi}{2})+1} \] (3)

Within a reasonable range, elastic deformation

\[ h_1'' = \left(\frac{2ht}{r}\right)^{1/2} \] (4)

Thus, \( h_1 \) may be written as

\[ h_1 = h_1' + h_1'' = \frac{t(1-\cos\alpha)}{\alpha(3-\frac{\pi}{2})+1} \left(\frac{2ht}{r}\right)^{1/2} \] (5)

Then, one can obtain the height of scallop (\( h_s \)) via

\[ h_s = r - (r^2 - (h/2\sin\alpha)^2)^{1/2} \] (6)

There are different influences of vertical force upon the F forming operation of SPIF. Figure 5 illustrates how the contact areas can be decomposed via projecting the region of contact to different communication planes. Calculating the decomposed areas normal to the tangential, axial and radial directions is the most critical step, as manifested in figure 5[7].

Figure 5. Graphic of decomposing the areas of contact
S_z side length can be written according to the geometric relationship.

\[ l_{1z} = (r^2 - (r - h_1)^2)^{1/2} \]  
\[ l_{2z} + l_{3z} = rsin\left(\alpha + \arccos\frac{r-h_h}{r}\right) \]  

One can obtain the contact area normal to the vertical direction via

\[ S_z = \frac{\pi}{4} l_{1z}^2 \left(1 + \frac{l_{2z} + l_{3z}}{l_{1z}}\right) = \frac{\pi}{4} \left[r^2 - (r - h_1)^2\right] \left(1 + \frac{r\sin(\alpha + \arccos\frac{r-h_h}{r})}{(r^2 - (r - h_1)^2)^{1/2}}\right) \]  

The feed per sheet can also be described as \( h - \text{Asin} 2\pi t \) when the simple harmonic vibration is applied to the plate \(^9\), therefore, the contact area \( (S_z) \) with vibration can be calculated using

\[ h' = \frac{t(1 - \cos \alpha)}{\alpha} + \frac{(2(\text{Asin} 2\pi ft) - t)}{r} \]  
\[ h_{sv} = \left(\frac{2(\text{Asin} wt) t}{r}\right)^{1/2} \]  
\[ S_z = \frac{\pi}{4} \left[r^2 - (r - h_{1v})^2\right] \left(1 + \frac{r\sin(\alpha + \arccos\frac{r-h_h}{r})}{\sqrt{r^2 - (r - h_{1v})^2}}\right) \]  

The cosine law is utilized for calculating the sheet metal thickness as follows:

\[ t = t_0 \cos \alpha \]  

The equivalent stress may be written as

\[ \bar{\sigma} = Ke^n \]  

The fitting parameters \( K \) and \( n \) can be described by the bulging test \(^8\), and the effective strain can be estimated from the experimental result. It is conceivable that the stress along the thickness directions acting on the small component can be represented by

\[ \sigma_t = -\frac{2}{\sqrt{3} t + 2.5t} \bar{\sigma} \]  

The axial forming force might be written as

\[ F_z = \sigma_t \times S_z \]  

Where:

- \( h \): Amount of the forming tool pressed
- \( h'_1 \): Thinning of the thickness of sheet at the plate bottom
- \( h'_1 \): The elastic deflection of sheet in the axial direction
- \( h \): Tool step depth
- \( t_0 \): Initial thickness of sheet metal
- \( t \): Actual thickness of sheet
- \( r \): Tool radius
- \( \alpha \): Wall angle of cone
- \( h_0 \): On the sheet surface, scallop height
- \( \sigma_t \): Through-thickness stress beneath tool
- \( \bar{\sigma} \): Effective stress
- \( F_z \): Axial forming force
4. Result and Discussion

4.1 Experimental axial forming force without vibration

A analytical–experimental comparative study was comprised at this work, for a simple cone part created by SPIF process. The magnitude of the other component of forming force (Fx, Fy) are small compare with the axial forming force component so the effect of vibration on (Fz) has been studded. Figure 6 elucidates the vertical forming forces during the process without vibrations; the force Fz applied upon the sheet was measured via S type load cell producing electrical charge proportionate with the sustained force. Via the charging amplifier unit, these signals of charge being transformed into resulted voltages that are then scaled up for measuring the forces. It can be observed that during the beginning phase, the vertical forces increase significantly and then begin to enter a steady state. In the first stage, the rapid rise in the early stage is due to the incidence of plastic deformation, material's strain hardening, and increase in contact region. A steady state is reached at a last point with the increase of the formation depth, when the influence of material thinning and strain hardening has been balanced.

![Figure 6. Axial force without vibration](image)

4.2 Forming force with frequency

During the experimental process, the vertical forces were estimated at applying a range of frequency. It is noticed from the figure that each point represents the value of the average axial force at a specific frequency in the forming plate layer; both sheets rebound as well as sheet deformation being initially comparatively slight through the operation of the sheet-metal forming. As a consequence, the vertical force was tiny. The sheet rebound and sheet deformation steadily became stable and attained the highest magnitude as the forming process improved. The vertical force has the highest magnitude at this time and reached a steady-state magnitude. A relation between mean vertical force and low frequency vibration through the operation of forming is evinced in figure (7). For further examining the low frequency vibration influence upon the reduction of force, the reduction rate of vertical force with vibration during the formation phase is illustrated in figure (7). It can be seen that the maximum
reduction rate in the axial force drops to (6.75%, 7.95%, 8.8%, 9.24%, and 11.64%) with frequency (20, 40, 60, 80, and 100) Hz, respectively. Figure (7) reveals that the rate of force reduction at the beginning is lower than the rate of force reduction at the end of the forming process depth, since the material is hammered by the forming tool, and the sheet at the initial phase has a high frequency of instantaneous load. At the later point, however, the material is deformed greater than the yield condition, and the sheet is still contacted by the tool. The vibration influence can be maximized after the rebound and stress reach equilibrium; therefore, the force reduction rate at the next phase is greater than that at the first step.

**Figure 7.** The mean vertical force with depth in z direction

Figure (8) show the comparison between analytical and experimental results. The value of experimental force at the point of maximum thinning of sheet metal. it is observed that there is difference between experimental and theoretical results, this difference is due to lack of theoretical knowledge of the forming mechanism because the forming process is very complicated and many parameter effect in the process.

**Figure 8.** Comparison between experimental and theoretical results
5. Conclusion

In the present work, the vibration effect upon the axial forming force during SPIF has been regarded. Depending on the obtained results, the main conclusions are:

1. The low frequency vibration effect was studied. The vibration enhancement surface quality by reducing friction force.
2. The forming force decreased after the addition of vibration. The best reduction in axial forming force at (100Hz) frequency.
3. The experimental axial forming force results are acceptable with the analytical solution.

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