Determination of forces in high speed blanking using FEM and experiments

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ABSTRACT

The increasing demand for micro-formed and stamped parts such as connectors in the electronic industry is forcing manufacturers to push the speed limit of conventional press technologies to improve throughput. Designing dies/tooling for higher speeds and obtaining extended tool life requires a thorough understanding of the process. This paper discusses an experimental study of the interaction between punch, stripper plate and sheet material at various blanking velocities up to 1600 mm/s. The effect of velocity on punching force is also studied. A methodology to obtain high strain and strain-rate dependent material flow stress data using blanking test and finite element modelling is presented.

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1. Introduction

High speed blanking and stamping are widely used in the electronics industry in the manufacture of components like pins and connector parts. High speed refers to strokes per minute (SPM) which can range from a few hundreds to a few thousands. The continuous growth of the electronic industry is driving manufacturers to investigate higher production speeds while maintaining high quality of the finished product. Precision stamping of thin and small components can be very challenging, especially at very high stamping speeds and velocities. Today, presses that can run at 800–1000 SPM at relatively large press strokes, such as 30–40 mm, and faster for shorter strokes. Therefore, it is important to understand the influence of speed on the dynamics and interaction between various tooling components in order to design robust dies and tooling for these speeds.

There is relatively little literature available in the field of high speed blanking. In most studies, the variation of punch load with speed has been studied. The relationship between other components of tooling at high speeds has not been looked into in much detail. Hirsch et al. (2011) measured various forces generated on the punch during blanking of a copper alloy, CuFeP 0.29 mm thick, using experiments for speeds up to 1000 SPM. However, the stroke length or blanking velocity was not mentioned in the paper. Cristhain et al. (1846) studied the effect of blanking velocity on blanked edge quality on various materials including steel, copper and aluminum alloys. Blankling velocities ranging from 900 mm/s to 3650 mm/s were studied. Some sheet materials show a higher sensitivity to blanking speed than others in terms of blanked edge quality. Caudilleire et al. (2013) conducted blanking tests up to velocity of 18 m/s and measured the punch load at different blanking velocities. The formation of adiabatic shear bands at very high cutting speeds was observed in this study. The effect of blanking velocity on blanked edge quality and blanking load can be found in these studies for high speed blanking. But the behaviour of stripper plate and reverse loading on the punch at high blanking speeds have not been given much attention.

There are various methods to obtain flow stress data of sheet materials. Tensile test is the most commonly used test to obtain material properties, in spite of the fact that it can be used to obtain the flow stress data (σ) for low strains (ε) only. The biaxial bulge test gives the flow stress data for strains higher than that obtained from tensile test as found by Gutscher et al. (2004). In addition, torsion tests and inverse methodology using operations like machining have also been suggested by various researchers. Ling (1996) suggested a method to extract the flow stress curves of materials beyond necking in tensile tests by using a combination of experimental load–stroke curve and iterations of FEM simulations. Although this is still uniaxial tensile test, flow stress curve is obtained for higher strains. Sartkulvanich et al. (2004) obtained flow stress data of materials using the machining process by using a combination of experiments and simulations. The advantage of obtaining flow stress through machining is that high strains and strain rates can be achieved. But better accuracy needs to be achieved for the process to become standardized. Gatteschi et al. (2008) suggested using cutting as a test method to obtain...
flow stress data of materials at room temperature. The significance of the coefficients \((K\) and \(n\)) of power (Hollomon) \((\bar{\sigma} = KE^n)\) law on the shape and maximum load of the experimental load–stroke curve in blanking is explained. In this study, a number of iterations of FE simulations with different \(K\) and \(n\) values are required. In addition, strain rate and temperature are important parameters to be considered in FE simulations of blanking. Kandis et al. (2011) also investigated shearing as a test to obtain flow stress data of sheet materials. However, the temperature and strain rate effects were not given enough importance. In addition, a methodology to match experimental and simulated load–stroke curves was not established.

One of the key differences between the different tests is not only the strain levels obtained, but also the stress state of the sheet materials. Hence, for an accurate representation of the deformation process in finite element simulations, it is important that the flow stress data of the sheet material input in the model was obtained under similar stress/deformation conditions as the process that is being simulated.

Hence, blanking can further be investigated as a test to obtain flow stress data of materials by (i) considering the effects of strain rate and temperature variation in the sheet and (ii) by establishing a methodology to match experimentally obtained and simulated load–stroke curves.

The main objective of the present study is to understand the punch–material and punch–stripper plate interactions in high speed blanking. The steps involved in this process include (i) identifying the various forces acting on the punch during an entire blanking cycle through experiments (ii) studying the influence of velocity on forces and vibrations through experiments and finite element analysis (FEA) (iii) investigating blanking as a test method to obtain material properties at high strains and strain rates using experiments and FEA.

### 2. Technical approach

The technical approach used in this study is as follows:

- Conduct blanking experiments at blanking velocities ranging from 20 mm/s to 1600 mm/s to study dynamic loading on the punch.
- Perform FEA of blanking using DEFORM 2D at quasi-static conditions and compare with experimental results.
- Use a combination of experimental results and FEA to develop a methodology to obtain strain rate dependent flow stress data for materials at high strains and strain rates.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Punch Material</td>
<td>Tungsten carbide (WC)</td>
</tr>
<tr>
<td>Diameters (mm)</td>
<td>1.5 (i) 32.44 (ii) 37.26</td>
</tr>
<tr>
<td>Tip</td>
<td>Flat</td>
</tr>
<tr>
<td>Sheet material, thickness</td>
<td>CS1100, 0.2 mm thick</td>
</tr>
<tr>
<td>Stripper pressure (MPa)</td>
<td>~1.3</td>
</tr>
<tr>
<td>Punch–die clearance (µm)</td>
<td>13 (6.5% sheet thickness)</td>
</tr>
<tr>
<td>Punch–stripper clearance (µm)</td>
<td>3</td>
</tr>
</tbody>
</table>

### 3. Experiments

#### 3.1. Tooling setup

Experiments were conducted using a 300 kN high speed mechanical press. The details of the tooling used in this study are shown in Table 1 and the schematic is shown in Fig. 1.

The stripper plate was spring loaded. Punch force was measured using a piezoelectric sensor (221803 from PCB Piezotronics, Inc.) and ram displacement was measured using a LK-H057 laser displacement sensor from Keyence Corporation. The data acquisition rate ranged from 50 kHz to 250 kHz depending on the press speed.

#### 3.2. Experimental procedure

Blanking experiments were conducted to measure the forces on the punch during the entire blanking cycle for various blanking velocities. Three cases (A)–(C) were studied. Experimental parameters used in each of the cases are shown in Table 2. A minimum of 20 readings were recorded for each velocity of each case.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>A</th>
<th>B</th>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distance from BDC at which punch touches sheet (mm)</td>
<td>0.86</td>
<td>0.86</td>
<td>5.38</td>
</tr>
<tr>
<td>Punch length (mm)</td>
<td>32.74</td>
<td>32.74</td>
<td>37.26</td>
</tr>
<tr>
<td>Range of punch velocity (mm/s)</td>
<td>20–800</td>
<td>20–800</td>
<td>40–1600</td>
</tr>
<tr>
<td>Stripper pinning the sheet during punching</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
</tr>
</tbody>
</table>

* Pinning refers to holding the sheet material down by applying force.
* Although the stripper plate was pinning the sheet, the punch was too long that pinning occurred after punching through the sheet.

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Fig. 1. Experimental setup for punch force measurements (schematic).
3.3. Experimental results

3.3.1. Punch force

Punch force and ram displacement are measured for the entire stroke. Various forces acting on the punch are identified during a blanking cycle, as shown in Fig. 2.

The stripper plate moves about 0.5 mm to pin the sheet while it interacts with the punch due to the very small clearance of ~3 μm between them. This is represented by the first peak shown in Fig. 2. The force when punch pierces through the sheet material is represented by blanking load in the figure, which is followed by the reverse loading of the punch. The punch moves to bottom dead centre (BDC) while frictional forces are generated between the punch and sheet material, which can be seen to change direction at BOC. The upward motion of the ram releases the stripper return springs (not shown in Fig. 1) and the stripper plate bounces back to its original position at a rate dependent on the ram velocity. Therefore, the amplitude of this vibration increases with ram speed. The influence of ram velocity on each of these forces is discussed below.

Blanking velocity, and hence strain rate, is an important parameter influencing the forces generated in blanking. Fig. 3 shows that the experimentally measured force required for blanking at 40 mm/s is 378 N while it is 522 N at 1616 mm/s. At higher blanking velocities (1200 mm/s and higher), vibrations in the punch and tooling cause a large variation in the measured blanking force. There is a 38% increase in the force required for blanking in the range of velocities studied. A potential explanation is that the hardening effect due to increase in strain rate has a greater influence on the blanking force than the local softening due to increase in temperature in the shearing zone, causing the force to increase with velocity. Interestingly, the reverse loading on the punch also shows increase with velocity, as seen in Fig. 3. The reverse loading is 13.5% of blanking force at 20 mm/s blanking velocity while it increases to 40% of blanking force at 808 mm/s. A possible explanation is that the elastic compressive forces stored in the punch during blanking are released more rapidly at higher speeds. This phenomenon illustrates the need for the punch and other related tooling to be designed to absorb the reverse loading in high speed blanking.

3.3.2. Stripper plate

The amplitude of stripper plate vibration during stripper plate pinning is mostly influenced by the characteristics of the spring that exerts a force on the stripper plate. The amplitude of vibration of the stripper plate vibration changes, depending on the stiffness of the spring and the velocity of the ram. This is reflected by the interaction between the lateral sides of the punch and the inner surface of the slot in the stripper plate, which exerts force on the punch. The vibration of the stripper plate causes lateral (perpendicular to punch motion) vibration on the punch. Fig. 4 shows that the force on the punch increases with increase in velocity until 933 mm/s after which it reduces and becomes independent of velocity. The amplitude of stripper plate vibration during pinning was significantly lower than that during unpinning. Fig. 5 shows that the amplitude of force exerted on the punch during unpinning is largely dependent on the ram velocity. The amplitude of punch force at higher speeds reaches 1300 N. The amplitude of these forces on the punch...
due to the interaction with the stripper plate purely depends on the stiffness of the stripper spring or rather the mechanism used for stripper plate motion.

Blanking load curve can be divided into various segments, as shown in Fig. 6 for Case A. The initial portion of the curve (a) and (b) corresponds to the elastic deflection of the punch, dies and sheet. The next portion of the curve (b) and (c) corresponds to rollover and shear, with the initial 0.02 mm corresponding to rollover and the remaining to shear. This is followed by fracture of the material, shown by region 'c-d-e' in the curve. This sudden drop in force leads to reverse loading of the punch as seen in region 'd-e'. Reverse loading refers to loading the punch in tension. While the punch is moving forward, it is initially under compression and elastic deformation. When the blank fractures the sudden release of compressive elastic energy in the punch causes the loading to reverse and the punch stresses to be in tension.

4. Finite element analysis of blanking (at low blanking velocity)

The accuracy of FE modelling of blanking heavily depends on the flow stress curve of the material, thermal properties and damage calculation to predict fracture. This study attempts to accurately simulate the blanking process using the software package DEFORM 2D. Since the process takes place in a very short period of time (in the order of a few milliseconds), heat transfer to the dies is negligible and hence not considered in the model. Temperature rise and heat conduction within the sheet material are taken into account. FEA of the blanking process corresponding to the experimental parameters in Case A and for a blanking velocity of 20 mm/s is conducted. FE simulations are conducted with the parameters shown in Table 1. Additional FE parameters are shown in Table 3.

The simulations were validated by comparing the simulated and experimental blanked edge zones, Table 4.

Fig. 7 shows the FE model and the computed maximum strains, strain rate and temperature distribution in the sheet before it begins to fracture. Since strains in the shear zone can be as high as 2.5 and higher, it is essential to provide the flow stress curves for up to such high strains. Strain rate can reach up to $10^3$ s even at very slow blanking speed of 20 mm/s.
Table 3
Additional simulation parameters used in FE simulation of blanking.

<table>
<thead>
<tr>
<th>Simulation parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sheet Material model</td>
<td>Plastic</td>
</tr>
<tr>
<td>Flow stress</td>
<td>Obtained using biaxial bulge test and extrapolated by fitting Hollomon’s equation $\sigma = 842.4 \times e^{0.00151}$ $\sim 100$</td>
</tr>
<tr>
<td>Number of elements along the thickness direction in the deformation zone</td>
<td>Adapted Rice &amp; Tracy (Sarkar/Vamshi et al. 2010)</td>
</tr>
<tr>
<td>Damage criteria used to simulate fracture</td>
<td>3</td>
</tr>
<tr>
<td>Critical damage value</td>
<td>Shear friction</td>
</tr>
<tr>
<td>Friction Type</td>
<td>0.1</td>
</tr>
<tr>
<td>Punch/die</td>
<td>Elastic</td>
</tr>
<tr>
<td>Material type</td>
<td>WC (E modulus = 650 GPa)</td>
</tr>
</tbody>
</table>

Table 4
Comparison of experimental and simulated blanked edge zones (Fig. 5, right).

<table>
<thead>
<tr>
<th>Zone</th>
<th>Simulation (µm)</th>
<th>Experiment (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Roll over ($Z_r$)</td>
<td>22</td>
<td>10</td>
</tr>
<tr>
<td>Shear ($Z_s$)</td>
<td>105</td>
<td>100</td>
</tr>
<tr>
<td>Fracture ($Z_f$)</td>
<td>71</td>
<td>64</td>
</tr>
</tbody>
</table>

5. Comparison of FEA and experimental results (at low blanking velocity)

The blanking load curve obtained experimentally is compared with results from FEA. From Fig. 8, it is seen that the forces compare very well with each other for most of the stroke because the blanking velocity is relatively low. Thus, flow stress obtained from static tests gives reasonable results. The results also suggest that the flow stress curve of the material used in the simulation is accurate enough to predict the force curve.

6. Development of high strain rate material flow stress model

Sections 4 and 5 discussed simulations conducted at quasi-static condition (velocity $\sim 20$ mm/s). However, in high speed blanking, the blanking speeds go up to 1.5 m/s and there is a corresponding increase in strain rate and temperature also. It is very challenging to obtain flow stress data at high strain rates for large strains. In this section, blanking is investigated as a potential test to obtain flow stress data for large strains and strain rates simultaneously and a methodology is proposed for the same.

The following assumptions/approximations are made in this methodology.

1. The strain distribution in the sheet does not vary with blanking speed (strain rate).
2. Strain rate is approximated to be a constant throughout the blanking process and changes only with blanking speed since the variation with speed is much greater than within the process.

The flow chart in Fig. 9 shows the proposed methodology to obtain flow stress curves for quasi-static blanking condition. Temperature effects are not taken into account in quasi-static blanking since there is only a very small temperature increase (Fig. 10).

High strain rate flow stress data can be calculated by using the combination of flow stress data obtained from Fig. 9 and experimental blanking force curves at higher speeds. A simple procedure for determining strain rate dependent flow stress data for high strains is shown in Fig. 11. The effect of temperature is not considered in this methodology because the maximum blanking force was found to occur at the very beginning of stroke, at which time, the temperature effects are small enough to be neglected. This also helps in separating the strain rate effect from temperature effect on the flow stress of the material.

7. Preliminary evaluation of the methodology

7.1. Flow stress curve for C51100

Applying the methodology described in Section 6, a strain rate dependent flow stress data was developed for C51100 using the
extrapolated bulge test data and blanking force data from experiments shown in Fig. 3. The ratio of maximum blanking force at various velocities to quasi-static velocity is calculated. The static flow stress curve obtained using the biaxial bulge test is increased by a factor equal to that ratio to obtain the flow stress curves at higher strain rates, shown in Fig. 12.

Since temperature is also a significant factor and temperature dependent flow stress data for this material was not available, relation between flow stress and temperature of pure copper from Nemat-Nasser and Li (1998) were used. The ratio of true stress at

**Fig. 10.** Points taken along the line of deformation to average stress, strain and temperature values.

**Fig. 12.** Flow stress for CS1100 obtained using the methodology developed in the present study.

**Fig. 9.** Flow chart to develop flow stress curve using blanking tests for low strain rate.

**Fig. 11.** Flow chart to develop flow stress curve using blanking tests for higher strain rate.
296 K to the true stress at higher temperature is calculated for different values of strains and averaged. This gives the factor by the true stress is scaled down due to the effect of temperature and is shown in Table 5.

For each strain rate, temperature dependent flow stress curves are calculated using Table 5. Hence, there is a total of 12 curves (4 strain rate dependent x 3 temperature dependent) are input as material property in DEFORM 2D for the simulations.

7.2. Simulation of high speed blanking

The flow stress curves obtained using the present methodology are used to simulate high speed blanking and compare the force curves with experimental results. Simulations were conducted for blanking speeds of 1060 mm/s and 1600 mm/s. The blanking forces are compared in Fig. 13. The forces compare fairly well. Since the experimental force had a component of vibration in it, it could not be expected to match perfectly well with simulations (which did not consider dynamic effects).

8. Conclusions and discussions

A comprehensive study was conducted to have a better understanding of high speed blanking at the tooling level. Punch–material interaction and punch–stripper plate interactions were studied. The experimental study yielded the following findings:

1. The velocity of blanking has a significant influence on forward and reverse loading.

2. The vibrations of the stripper plate during unpinning apply lateral force on the punch, which could influence the strength and life of slender punches.

The following results are obtained from the FE study:

1. Modelling of high speed blanking requires both temperature and strain rate dependent material model at high strains.
2. Blanking itself could be used as a test to generate material flow stress data at high strains and strain rates.

References


