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Determination of forces in high speed blanking using FEM and experiments

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The increasing demand for micro-formed and stamped parts such as connectors in the electronic industry is forcing manufacturers to use press speeds of more than a couple of thousands of Strokes per Minute (SPM). Designing dies/tooling for such high 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 1600mm/sec. 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 modeling is presented.

Punching; Finite Element Modeling (FEM); high velocity

1. Introduction

High speed blanking and stamping is 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 4000 SPM are available. 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 stamping. Hirsch et al. [1] studied the effect of speed on the various forces generated on the punch during blanking of a copper alloy using experiments. Forces were measured for speeds up to 1000 SPM. Grünbaum et al. [2] studied the effect of blanking velocity on blanked edge quality on various materials including steel, copper and aluminium alloys. Blanking velocities ranging from 0.9m/sec to 3.65m/sec were studied. However, a combination of high press speed (SPM) and high blanking velocity was not studied in either case.

The objective of this study is to understand the punch-material and punch-stripper plate interaction 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:

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

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 Figure 1. The stripper plate was spring loaded.

Table 1: Tooling Parameters Used in Experiments

Parameters	**Value**
Punch	
- Material	Tungsten Carbide (WC)
- Diameter	1.5mm
- Lengths	(i)32.74mm (ii) 37.26mm
- Tip	Flat
Sheet	C51100, 0.2mm thick
Stripper Pressure	~1.3MPa
Punch-Die Clearance	13μ (6.5% sheet thickness)
Punch-Stripper Clearance	3μ

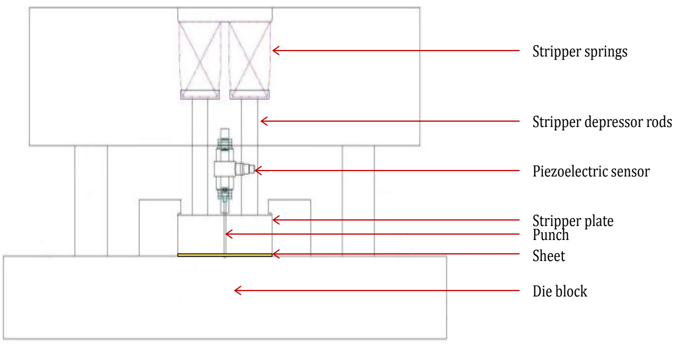

Figure 1: Experimental setup for punch force measurements (schematic)

Punch force was measured using a piezoelectric sensor (221B03 from PCB Piezotronics) and ram displacement was measured using a Keyence LK-H057 laser displacement sensor. The data acquisition rate ranged from 50 – 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, B, 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 2: Experimental Parameters

	A	B	C
Distance from BDC at which punch touches sheet (mm) / Punch Length (mm)	0.86/ 32.74	0.86/ 32.74	5.38/ 37.26
Range of punch velocity tested (mm/sec)	20-800	20-465	40-1600
Stripper pinning* the sheet during punching	Yes	No	No**

*Pinning refers to holding the sheet 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.

3.3. Experimental results

Various forces acting on the punch are identified during a blanking cycle, as shown in Figure 2.

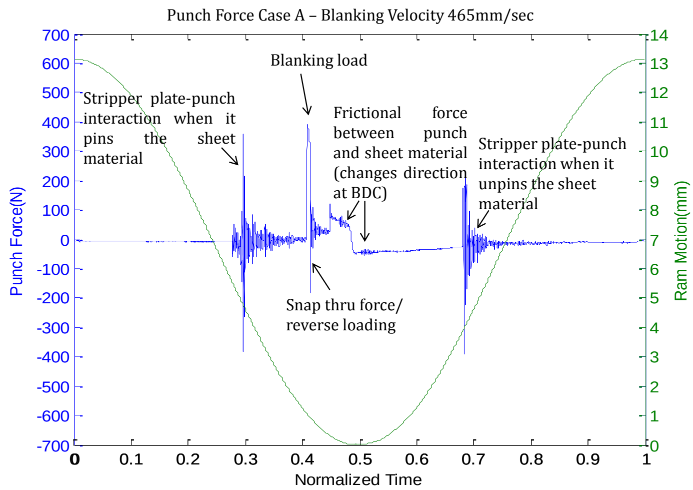

Figure 2: Forces acting on the punch during blanking

The stripper plate moves about 0.5mm to pin the sheet while it interacts with the punch due to the very small clearance of ~3μ between them. This is represented by the first peak shown in Figure 2. The force when punch pierces through the 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, which can be seen to change direction at BDC. The upward motion of the ram releases the stripper return springs (not shown in Figure 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 blanking 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. Figure 3 shows that the experimentally measured force required for blanking at 40mm/sec is 378N while it is 522N at 1616mm/sec. There is a 38% increase in load for the range of velocities studied. A potential explanation is that the hardening effect due to increased strain rate overcomes the local softening due to temperature reached 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 Figure 3. The reverse loading is 13.5% of blanking force at 20mm/sec blanking velocity while it increases to 40% of blanking force at 808mm/sec. A possible explanation is that the elastic compressive forces stored in the punch during blanking are released more rapidly at higher speeds. This phenomenon emphasises the need for the punch and other related tooling to be designed to absorb the reverse loading in high speed blanking.

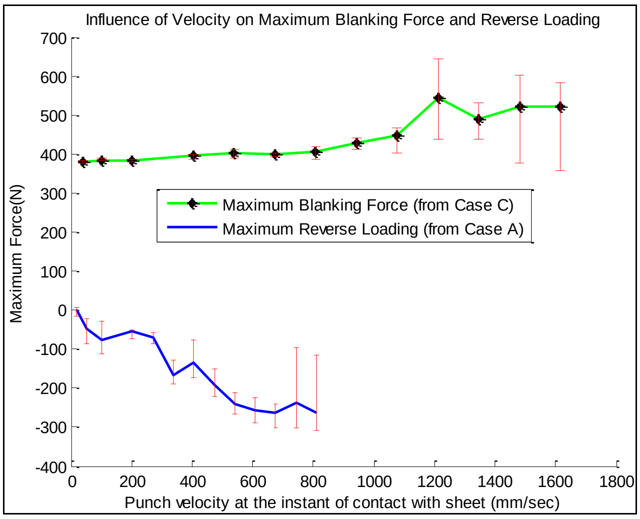

Figure 3: Influence of velocity on maximum blanking force and maximum reverse load

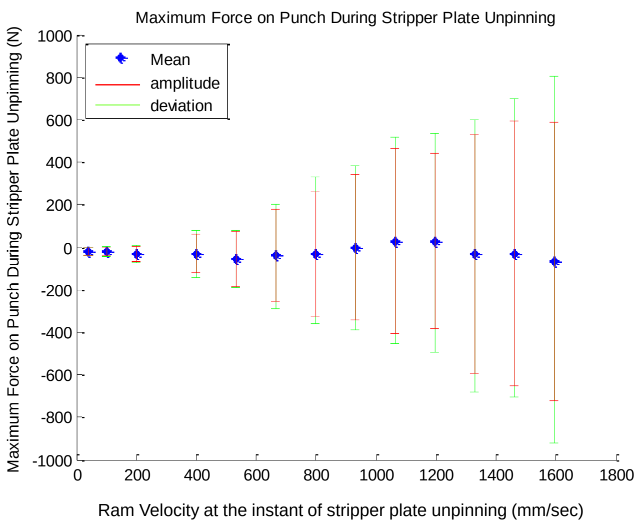

Figure 4: Influence of velocity on vibrations during stripper unpinning

The amplitude of vibration during stripper plate pinning is mostly influenced by the characteristics of the spring. The amplitude of vibration during pinning was significantly lower than that during unpinning. Figure 4 shows that the amplitude of vibration during unpinning is largely dependent on the ram velocity. The amplitude of punch force at higher speeds reaches 1300N. These vibrations are experienced on the lateral face of the punch.

Blanking load curve can be divided into various segments, as shown in Figure 5 for Case A. The initial portion of the curve (a-b) corresponds to the elastic deflection of the punch, dies and sheet. The next portion of the curve (b-c) corresponds to rollover and shear, with the initial 0.02mm corresponding to rollover and the remaining to shear. This is followed by fracture of the material, shown by region 'c-d' in the curve. This sudden drop in force leads to reverse loading of the punch as seen in region 'd-e'.

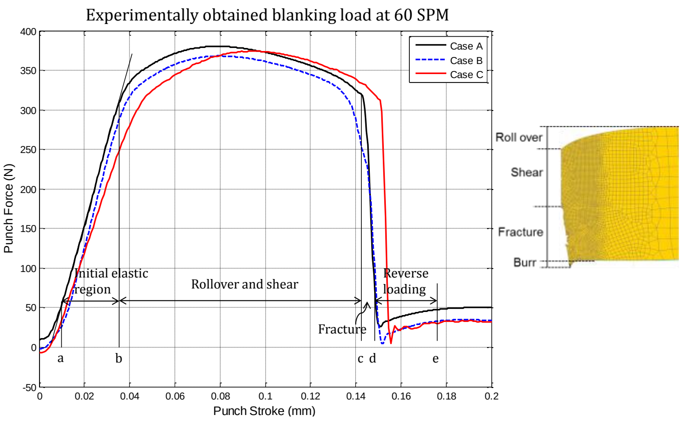

Figure 5: (left) Blanking load curve at 60 SPM; (right) blanked edge profile

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 blanking velocity of 20mm/sec is conducted. FE simulations are conducted with the parameters shown in Table 1 . The sheet is modelled as a plastic object and the punch as an elastic object. Adapted Rice and Tracy (taken from the results from [3]) is the damage function used to model fracture in the sheet, and the critical damage value used is 3.

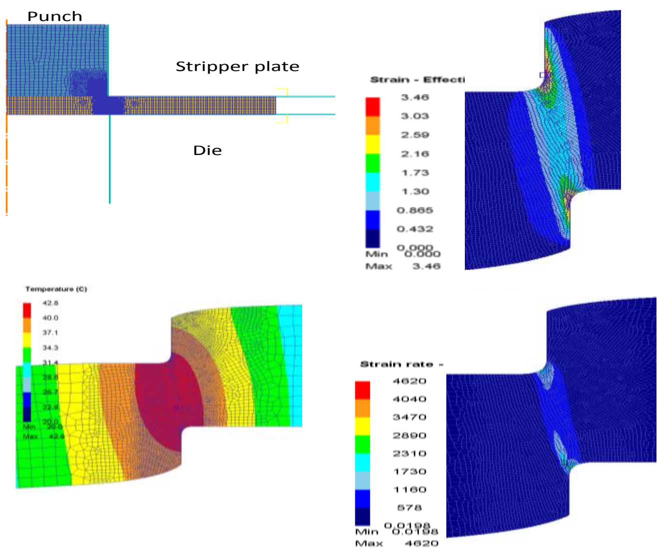

Figure 6: (From top left clockwise) FE model setup; strain distribution; strain rate distribution; temperature distribution in the sheet (at 0.1mm punch stroke / sheet thickness = 0.2mm)

The flow stress curve for C51100 was obtained using static biaxial bulge test and used in the simulations. The flow curve is extrapolated by fitting Hollomon's equation ($\sigma = 842.4\varepsilon^{0.1355}$) to the experimental data.

Figure 6 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/sec even at very slow blanking speed of 20mm/sec.

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

The blanking load curve obtained experimentally is compared with results from FEA. From Figure 7, 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.

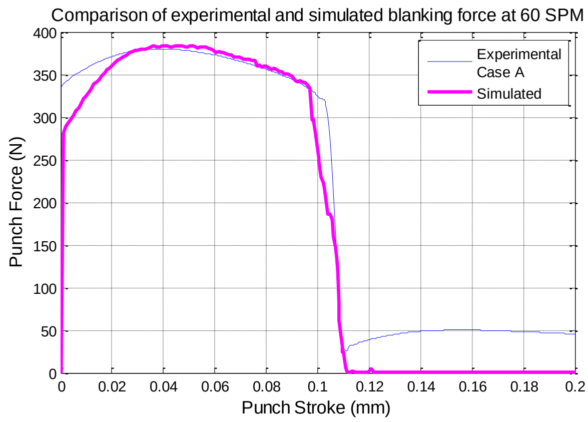

Figure 7: Comparison of experimental and simulated blanking load [The initial elastic portion of the experimental curve was not included in the comparison since it could not be replicated in the simulation]

6. Development of high strain rate material flow stress model

Sections 4 and 5 discussed simulations conducted at quasi-static condition (velocity – 20mm/sec). However, in high speed blanking, the blanking speeds go up to 1.5m/sec 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.

- The strain distribution in the sheet does not vary with blanking speed (strain rate).
- 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 Figure 8 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 increase.

Obtain blanking force-stroke curve from experiments conducted at low speed (quasi-static condition)

↓

Conduct blanking simulation using extrapolated flow stress curve obtained using uniaxial or biaxial test.

↓

Obtain the force F_s, average stress σ_s, average strain ε_s, average strain rate $\acute{\varepsilon}_s$ and average temperature τ_s in the sheet at small intervals 'i' of stroke. (refer Figure 9 on how the average values were obtained)

↓

Compare the experimental (F_e) and simulated force (F_s) at each step 'i' of stroke

↓

At each step 'i', if $F_s \neq F_e$ → $\sigma_{s\ new} = \sigma_s*(F_e/F_s)$

↓

Average (of all steps 'i') strain rate for the process $\acute{\varepsilon}_{speed}$ is calculated. Flow stress curve for $\acute{\varepsilon}_{speed}$ is obtained.

Figure 8: Flow chart to develop flow stress curve using blanking tests for low strain rate

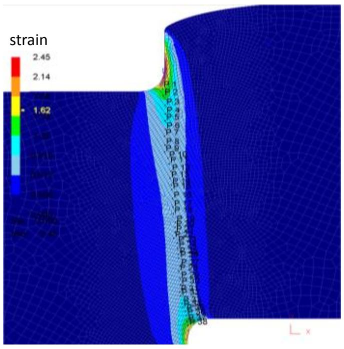

Figure 9: Points taken along the line of deformation to average stress, strain and temperature values

High strain rate flow stress data can be calculated by using the combination of flow stress data obtained from Figure 8 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 Figure 10. 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.

Obtain blanking force-stroke curve from experiments conducted at higher speeds corresponding to various strain rates.

↓

For each of the strain rates $\acute{\varepsilon}$, find the ratio of maximum blanking force at higher strain rate to maximum blanking force at quasi-static condition

Force Ratio = $F_{max\ \acute{\varepsilon}} / F_{max\ e}$

↓

Scale the flow stress curve at quasi-static condition (obtained from Figure 8) by the Force Ratio obtained in the previous step. This gives the flow stress data for the material at higher strain rates.

Figure 10: Flow chart to develop flow stress curve using blanking tests for higher strain rate

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 Figure 3. The ratio of maximum blanking force at various velocities to quasi-static velocity is calculated. The static flow stress curve obtained using the bulge test is increased by a factor equal to that ratio to obtain the flow stress curves at higher strain rates, shown in Figure 11.

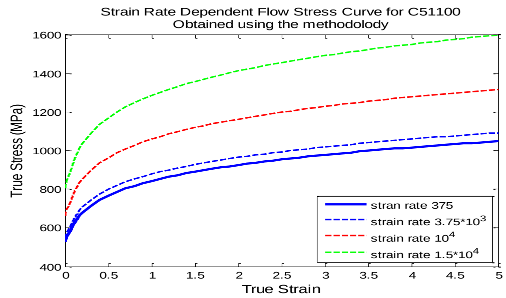

Figure 11: Flow stress for C51100 obtained using the methodology

7.2. Simulation of high speed blanking

The flow stress curve obtained using the methodology is used to simulate high speed blanking and compare the force curves with experimental results. 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 [4] were used. Simulations were conducted corresponding to 1060mm/sec and 1600mm/sec. The blanking forces are compared in Figure 12. 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).

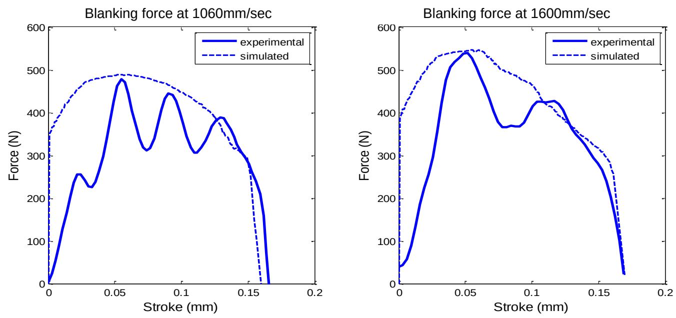

Figure 12: Comparison of blanking force obtained from simulation and experiments

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:

(i) The velocity of blanking has a significant influence on forward and reverse loading

(ii) 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:

(i) Modelling of high speed blanking requires both temperature and strain rate dependent material model at high strains.

(ii) Blanking itself could be used as a test to generate material flow stress data at high strains and strain rates.

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