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Finite-element and experimental analysis of dynamic behaviours of a micro-stamping tool system

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Abstract As demands on the forming of micro-products increase, ensuring the high-quality design of machine–tool systems becomes increasingly more important. This is particularly due to a need to address smaller geometries and finer tolerance requirements, compared to those of conventional forming. Finite-element (FE) simulation of the dynamic behaviour of machines and tools is particularly useful for supporting design optimisation. Detailed finite-element modelling of stamping tool systems has, however, not been addressed previously. Difficulties tend to arise when many tool parts need to be considered in the modelling. In this paper, dynamic analysis of a micro-sheet-forming system driven by a linear motor is presented. Parameters that influence dynamic behaviours of the micro-stamping tool were investigated using the finite-element analysis and the results of experimental measurement. The findings provide useful information for the improvement of the design of micro-stamping tools as well as for the design of micro-forming-machine systems.

Keywords Micro-stamping · Stamping tool · Dynamic response · Finite-element analysis · Forming experiment

1 Introduction

Damage to the punches is one of the major problems during high-speed stamping. In order to avoid punch damage and to achieve high precision during high-speed stamping, dynamic response of the tools was seen as a critical parameter [1, 2]. At the same time, for a set of stamping tools that hold multi-punches, influence of the asymmetrical cutting forces on the precision of stamping, due to use of multiple punches which may not be symmetrical or symmetrically arranged, also needs to be considered. In addition, for improving the performance of the whole forming machine system, the exciting forces transferred from the stamping tool to the machine system have to be qualified. The influence of the springs used in tooling on the dynamic behaviour of the tool system itself also needs to be considered. These factors are particularly important for micro-forming since manufacturing precision is a key issue to be addressed in the forming of micro-products [3, 4].

2 Structural characteristics and functions of the stamping tool

A stamping tool set and the coordinate system are shown in Fig.1. Tens of components are connected together by bolts, bearings, springs and push-fit assemblies. This tool set may be separated into an upper half and a lower half. It is driven by a linear motor via a ram, the latter being guided by a guiding bridge that is connected to the forming machine frame. The lower half is connected to the forming machine bed by means of four bolts located near to the four corners. The ram, which is controlled by the linear motor, contacts with the top plate of the tool. Two groups of springs connect the top plate to the punch guide plate, and the punch holder plate to a blank holder, respectively. For testing purposes, two different pairs of the punches and dies are used to produce two different shapes (stamping geometries) of component and are the key parts of a single-stage stamping tool set for forming experiments.

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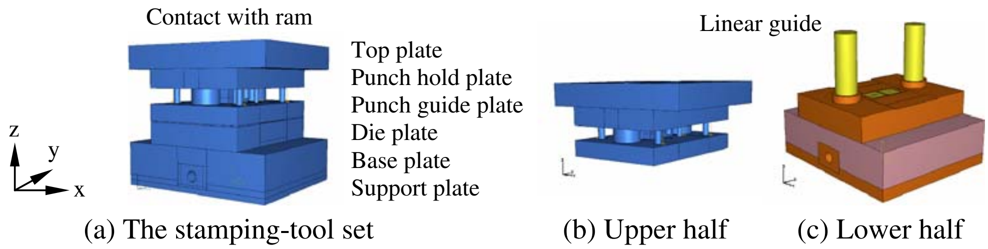
Fig. 1 a–c Micro-stamping tool set



3 The dynamic response analysis

The dynamic response analysis focuses on the response of the punches, the boundaries and moving components such as the blank holder and the punch guide plate. The force equilibrium of a real physical structure as a function of time is expressed by the following equation:

$$[M]\left\{\ddot{u}\right\}+[C]\left\{\dot{u}\right\}+[K]\{u\}=\{F(t)\} \tag{1}$$

where

$[M]$	is the total mass matrix of the structure
$[C]$	is the damping matrix of the structure
$[K]$	is the stiffness matrix of the structure
$\{u\}$	is the vector of nodal displacements
$\{\dot{u}\}$	is the vector of nodal velocities
$\{\ddot{u}\}$	is the vector of nodal accelerations
$\{F(t)\}$	is the vector of applied forces

ABAQUS/Explicit utilises an explicit direct-integration method to solve this dynamic equation. The explicit method is conditionally stable: it needs to use a small time increment (Computers and Structure, available at: http://www.csiberkeley.com/support_technical_papers.html) [5]. The procedure employed to analyse the dynamic response of the stamping tool involves the following aspects:

1. *Geometrical modelling*: all the components are built separately and then assembled. In the finite-element simulation, the tie technique was used to simulate screw and push-fit connexions; the dynamic surface-to-surface contact technique was used to simulate the contact between components; and the axial connector was used to simulate spring connexions.
2. *Material models*: Carbon Steel C40 and AISI D2 Tool Steel were used for the tool parts. Four R204205 springs and four R204104 springs were used.
3. *Boundary conditions*: the displacement of the ram was assumed to be $u=A_0\,[\cos(\omega t)-1]$. Four bolts were used to attach the stamping tool to the supporting plate of the machine bed.
4. *Contact model*: in surface-to-surface contact, hard contact was assumed for normal behaviour of the contacts and different friction coefficients were used for tangential behaviour. Finite sliding was allowed in the model.
5. *Meshed model*: C3D8R elements were used for most of the structure. A suitable transition of element density was made to achieve high accuracy.

Eight models were analysed and the results compared. The key variable parameters in the models are listed in Table 1. C1 is the friction coefficient of the contact between the tool components; C2 is the friction coefficient for the contact between the blank holder and the sheet metal and C3 is the friction coefficient of the rollers (Rolling Bearing Friction, available at: http://www.roymech.co.uk). A_0 is the amplitude of the ram movement.

Table 1 Dynamic analysis models of the micro-stamping tool

Model	Frequency of linear motor (Hz)	Cutting force	Force factor	C1	C2	C3	A0
1	16	Yes	3	0	0	0	1.7565
2	16	No	0	0	0	0	1.7565
3	8	No	0	0	0	0	1.7565
4	16	Yes	2	0.05	Rough	0	1.7565
5[a]	16	No	0	0	Rough	0	1.7565
6	16	No	0	0	Rough	0.0011	2.7565
7	16	No	0	0	Rough	0.0011	1.4
8	16	No	0	0	Rough	0.0015	1.4

*0.02 degrees of inclination of the ram during the stamping was assumed, which amount could in practise be caused by geometric eccentricity of the machine/tool structures, eccentric loading due to machine frame deflections, etc.

Fig. 2 The micro-sheet-forming machine system used for the experiment

4 Experimental measurement

The punch guide plate guides the movement of the punches during the stamping process. The aim of the experiment was to measure the vertical movement of the punch guide plate at different working frequencies and different amplitudes of ram movement. Non-contact measurement of the vertical response was performed using an optical sensor—RGH24Y—which has a resolution of 0.1 µm. The RGH24Y was fixed onto the punch guide plate, and a reference plate with a gold-strip scale was fixed onto the base plate. The prototype of a micro-stamping machine (developed at the University of Strathclyde), with the RGH24Y mounted onto the stamping tool, is shown in Fig. 2. The influence of roller friction on the dynamic response of the punch guide plate was investigated at a design value of A_0=3 mm, the results being shown in Fig. 12, whilst the results for A_0=6 mm and A_0=3 mm with dry rollers are shown in Fig. 8. Samples taken at 16 Hz for an actual value of A_0= 1.35 mm and 15 Hz for an actual value of A_0=2.88 mm are shown in Figs. 9 and 10, respectively. The design amplitude of ram movement A_0 and its actual value are slightly different, as the latter value is controlled by the proportional–integral–derivative (PID) parameters of the control system of the linear motor.

5 Findings of the dynamic analysis

The main dynamic response characteristics of the eight models of the stamping tool and the results of experimental measurement are presented as follows.

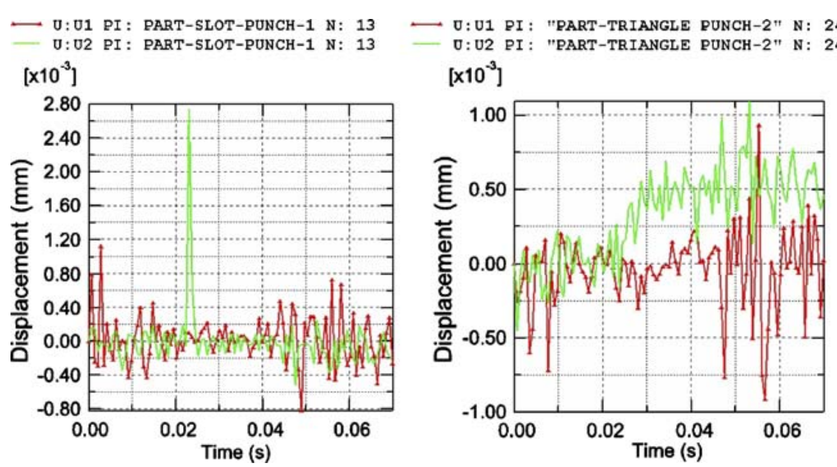
5.1 Response of the punches

Figure 3 shows the results of the displacements of the punches in the *x*- and *y*-direction (horizontal plane) in model 1. Cutting force acts from 0.0235 to 0.0241 s. It is seen clearly, from its movement away from its original balance in the *y*-direction, that during cutting the triangular punch is less stable than the rectangular punch: this phenomenon occurs also in model 4.

5.2 Response of the blank holder

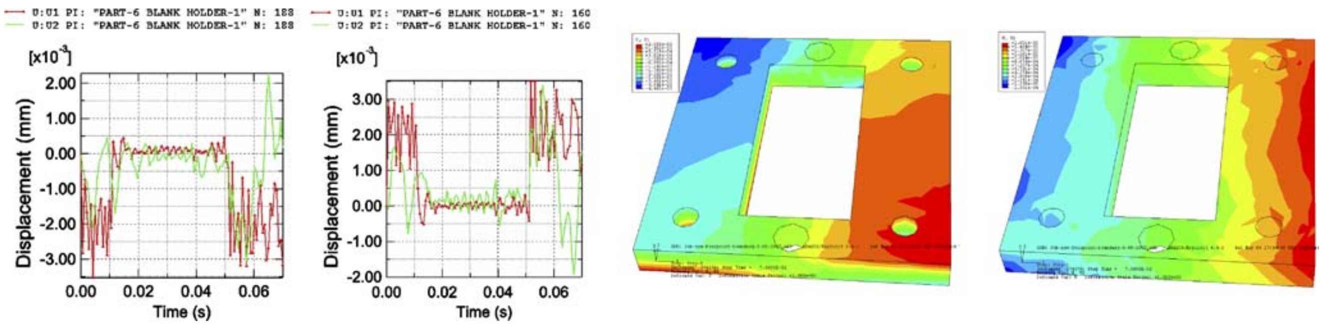
Figure 4 shows the displacement response of the blank holder in the *x*-direction and the *y*-direction in model 1.

Fig. 3 Response of the punches



Rectangular punch

Triangular punch



(a) Node 188 (b) Node 160 (c) x direction (d) y direction

Fig. 4 a–d Response of the blank holder

The blank holder makes contact with the strip from 0.0112 to 0.0511 s. The nodes 188 and 160 are symmetrical about the *y*-axis: Fig. 4a, b shows their displacements in the directions *x* and *y* against time. Figure 4c, d is the contour plots of the blank holder: the movement of the blank holder is a twisting vibration about the *z*-axis (vertical direction). The blank holder is unstable before and after making contact with the strip. The influence of this on the response of the punches can be seen in Fig. 3: similar results are obtained for the other models.

5.3 Response of the boundary of the support plate

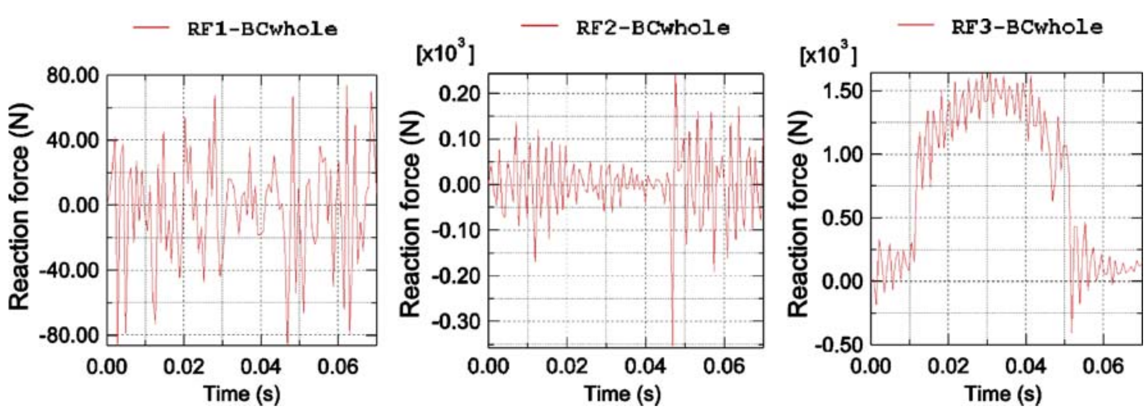
The reaction forces RFX, RFY and RFZ on the fixed boundary of the supporting plate are shown in Fig. 5 for a working frequency of the linear motor of 16 Hz in model 2, where RFX, RFY and RFZ refer to the reaction force in the directions *x*, *y* and *z*. The average frequency of the reaction force is about 30 times that of the working frequency of the linear motor, the frictional contact between the components slightly reducing the frequency of the reaction force.

5.4 Response of the punch guide plate

The same phenomena in the response of the punch guide plate have been found from FE analysis and experimental measurement. The punch guide plate is initially in contact with the upper surface of the die plate. It then moves up during the stamping process, the vertical displacement increasing non-linearly with increase in the amplitude of the ram movement and working frequency. FE simulation results of the vertical response of the punch guide plate for A_0=1.4 mm and A_0=2.76 mm are shown in Figs. 6 and 7, respectively, whilst the results of experimental measurement are shown in Figs. 8, 9 and 10.

5.5 Response of the roller

The results of FE simulation of the response of the roller for different values of the friction coefficient are shown in Fig. 11, whilst the results of experimental measurement of the influence of friction on the response of the punch guide plate are shown in Fig. 12. The friction of the roller also has a significant influence on the PID parameters of the control system of the linear motor.



(a) RFX (b) RFY (c) RFZ

Fig. 5 a–c Reaction forces on the fixed boundary

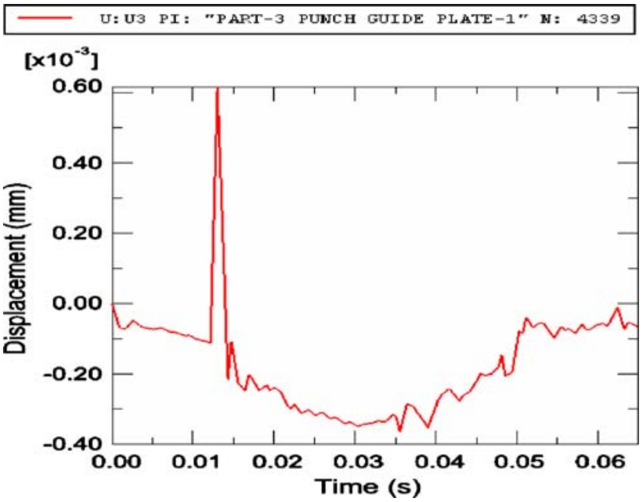


Fig. 6 Response of the punch guide plate: A_0=1.4 mm, 16 Hz

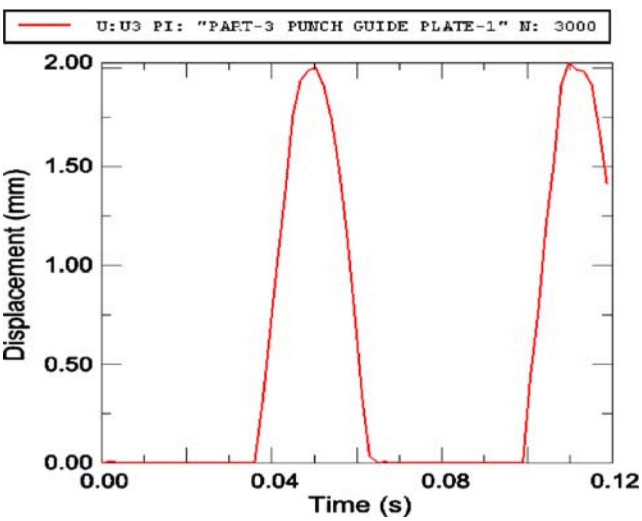


Fig. 7 Response of the punch guide plate: A_0=2.76 mm, 16 Hz

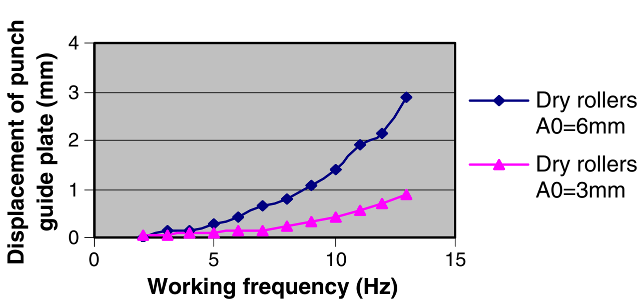


Fig. 8 Response of the punch guide plate

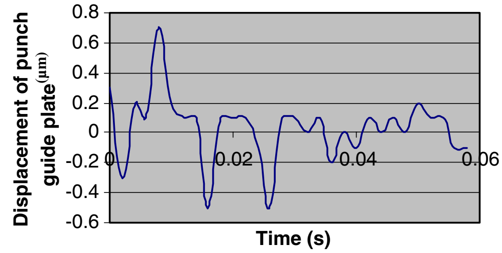


Fig. 9 Response of the punch guide plate: A_0=1.35 mm, 16 Hz

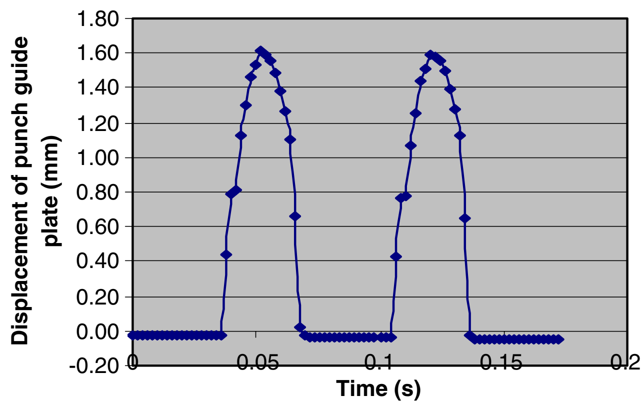


Fig. 10 Response of the punch guide plate: A_0=2.88 mm, 15 Hz

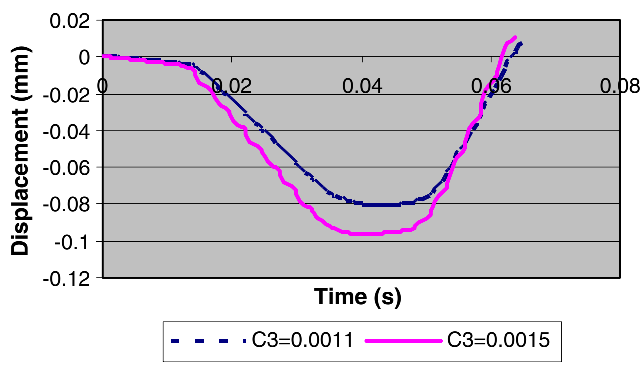


Fig. 11 Response of the roller: A_0=1.4 mm, 16 Hz

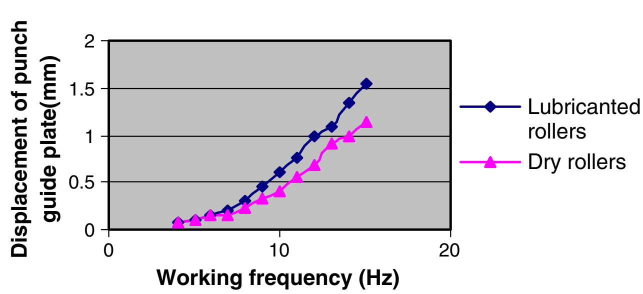


Fig. 12 Response of the punch guide plate: A_0=3 mm

6 Discussion and conclusions

The analysis of the findings enabled the following to be identified as of particular relevance to tool and machine design for micro-stamping:

1. The dynamic reaction forces acting on the connexion between the support plate and the micro-forming machine have a frequency greater than the working frequency of the linear motor. This frequency will be transferred to the system during the forming process. The value is very close to the natural frequencies of the lower modes of vibration of the machine in the absence of a rubber base. Therefore, the response frequency of the stamping tool should be taken as a crucial parameter in the design of a micro-forming-machine system.
2. When using spring force to control moving components such as the blank holder, the local vibration excites the whole stamping tool and significantly influences the dynamic response of the punches. To improve the design, it is suggested that more control of their dynamic performance should be exerted on moving components such as the blank holder.
3. Differences in punch geometries result in an imbalance of the cutting forces between the punches, giving rise to differences in their dynamic behaviour. In the cases studied, the smaller punch tends to move away from its original position, and continual high-speed stamping leads to increasingly greater offset in displacement. This is possibly the main reason why, as the cutting speed was increased, such a punch was always damaged early. This has to be taken into account when punches are designed for high-speed stamping.
4. The punch guide plate moves up during the stamping process. Both the amplitude of ram movement and the working frequency have a significant influence on this movement. An unstable punch guide plate will generate an exciting force on the punches, reducing the precision of the tooling. Because high speed is the target of this micro-stamping tool, the amplitude of ram movement should be made as small as possible in the design of the whole system.
5. The guiding rollers should be lubricated during the stamping process. Difference between the design amplitude and the actual amplitude of ram movement is greater in the absence of lubrication. This may cause the punch to be unable to cut material correctly in high-speed stamping. Reducing the friction of the roller can make the whole system easier to control, especially when material forming and material feeding need to be activated at the correct time.

The findings presented above formed a basis for improving the micro-stamping tool and machine–tool connexion design for the forming of micro-sheet components.

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