

# Finite Element Structural Analysis of a Low Energy Micro Sheet Forming Machine Concept Design

**A.R. Razali\*, C.T. Ann, A.F. Ahmad, H.M. Shariff, N.I. Kasim, M.A. Musa**

Faculty of Mechanical Engineering, Universiti Malaysia Pahang,  
26600 Pekan, Pahang, Malaysia

\*Email: akhtar@ump.edu.my

**Abstract.** It is forecasted that with the miniaturization of materials being processed, energy consumption will also be 'miniaturized' proportionally. The aim of this research is to design a low energy micro-sheet-forming machine for the application of thin sheet metal. A few concept designs of machine structure were produced. With the help of FE software, the structure is then subjected to a forming force to observe deflection in the structure for the selection of the best and simplest design. Comparison studies between mild steel and aluminium alloys 6061 were made with a view to examine the most suitable material to be used. Based on the analysis, allowable maximum tolerance was set at  $2.5\mu\text{m}$  and it was found that aluminium alloy 6061 suffice to be used.

## 1. Introduction

Rapid development of micro-manufacturing technologies for the manufacture of individual parts and systems was mainly driven by the increased demands on micro-products. Development works in the micro-manufacturing technologies includes development of new manufacturing processes, tools and machineries. Manufacturer nowadays still largely relies on conventional techniques based on materials removal, either by thermal, mechanical or by chemical means. To-date, tremendous efforts have been made to improve efficiency of micro-manufacturing technologies specifically in its processes [1-2]. The efforts however, have not resulted radical change to the technologies but created a stigma of micro-manufacture as an 'expensive' and 'wasteful' business. Conversion of micro-materials into end products by high-rate plastic deformation (micro-forming) would address two key issues which are of importance for the industry, namely, reduction of manufacturing costs and improvement of product quality [3-4]. Besides, the need is proportional to the complexity of forming of micro-materials which requires good understanding of machines and processes at micro-scale.

A research group elsewhere [4] was making significant efforts in this field with a view to achieve the goals. A micro-sheet-forming machine has been developed by the group and proven to have capability of producing micro-products with consistent accuracy and precision [5]. The machine used linear motor to drive the forming ram/punch. It was reported that 5kN of stamping force was achieved. Forming capability was at 840 parts per minute. The machine required 3 phase 415VAC electricity supply to work. The story had demonstrated success in micro-machines development, however, effort to tackle energy conservation was not addressed. It is expected that with the miniaturization of material being processed, energy consumption is also 'miniaturized' proportionally. Miniaturization of part with a scale of 100:1, could also translate the energy reduction within the same ratio [6].

A low power micro-sheet-forming machine which uses hundred times less energy than its conventional counterpart is practically a direct solution to address the issue. This is achieved by using a low power actuation device to perform the forming process. Solenoid is one of the promising solution to be used for the development work addressed here. With rated power of 12-24VDC, the solenoid is capable of



producing kilonewton force over millimeters' distance. This setup could be a practical solution to reduce energy usage while performing sheet forming process.

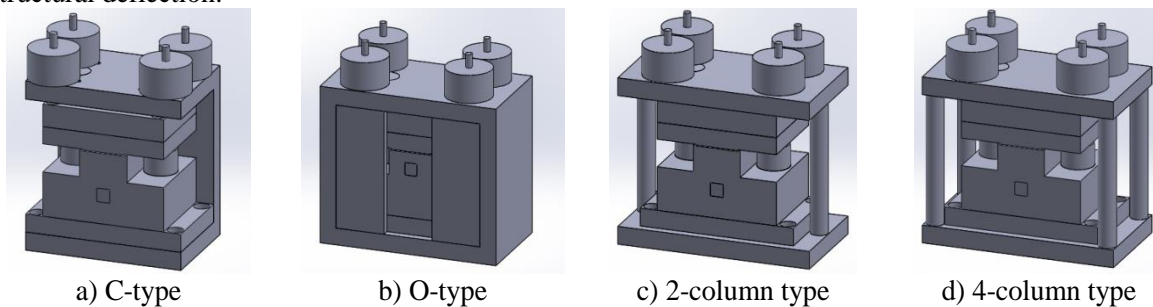
## 2. Machine Design Specification/Consideration

The following factors were considered when designing the machine specifications: forming of thin sheet metal with thickness of less than 100 $\mu$ m; forming tolerance is 5~10 % of the strip thickness (i.e. 50 $\mu$ m thick strip was used); electricity power used is direct current approximately 12-24VDC; flexible design for easy set-up and changes of the forming tools, fixtures, part carrier and parts collection.

## 3. Machine System Development

### 3.1 Machine Frame

Various machine structural designs were examined. Thus, various machine concept layouts were created as depicted in Figure 1(a) to (d). Evaluation of the various machine concepts was carried out by reviewing deflection on each part of the frames, and then is followed by eliminating the weakest structure. The analysis was carried out by exerting 200N of force at four different points on top of various frame concepts with a view to simulate the forming force. O-frame machine design was selected as it produced the lowest structural deflection.



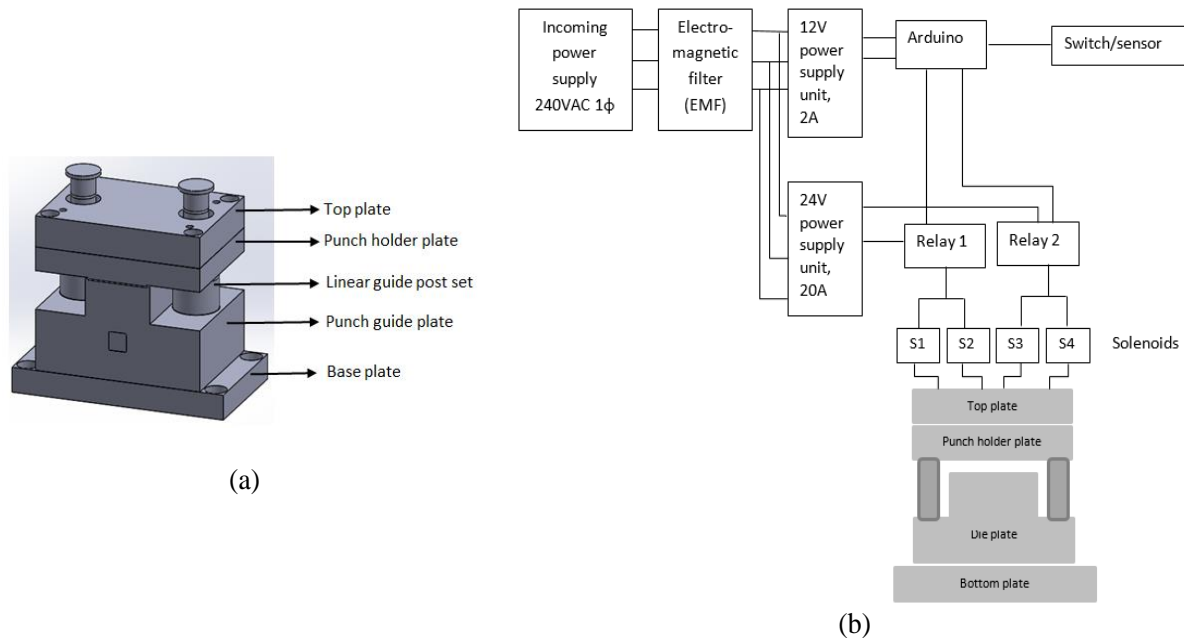
**Figure 1.** Various machine frame design.

### 3.2 Tool Development

The tooling system basically consists of an upper and a lower half die with die-inserts (Figure 2a). The lower half die was fixed to the forming machine frame. Upper and lower half dies were linked together with two linear guide posts. The guide posts were connected to the upper die by push-fit assembly. Four springs were used to link between blank and punch holder plates. The die insert located at the middle of punch guide plate and it is aligned with the punch with the use of the linear guide posts. A tunnel shaped drawer was made below the die-insert plate for parts collection.

### 3.3 Control System

Linear actuation was realized by using four linear solenoids as depicted in Figure 2(b). Each solenoid has a capability of thrusting 170N of force at 25% duty cycle. The solenoids were powered by 24VDC power supply unit and controlled with a pair of solid state relays. Each relay connected to two solenoids and controlled by a microcontroller. The system receives 240 VAC as an incoming electricity supply and filtered by an EMF filter. Filtered power source is fed to an energy meter to monitor energy usage by the machine. Figure 2(b) shows the schematic illustration of connection of the main machine elements and system for control.



**Figure2.** (a) Machine and tooling structure and (b) Architecture of machine control system.

#### 4. Finite Element Analysis

FE analysis was conducted to study each individual part and with the aim to focus on the deflection of the machine frame and moving structures (top and punch guide plate). The forces exerted simulate the forming force of the solenoid. A comparison study was made to observe and analyze deflection occurred on two different materials; Aluminium alloy 6061 and mild steel. The deflection tolerance used was  $2.5\mu\text{m}$  like the forming tolerance. By taking strip thickness as  $50\mu\text{m}$  for example, the deflection preferably not be greater than  $2.5\mu\text{m}$ .

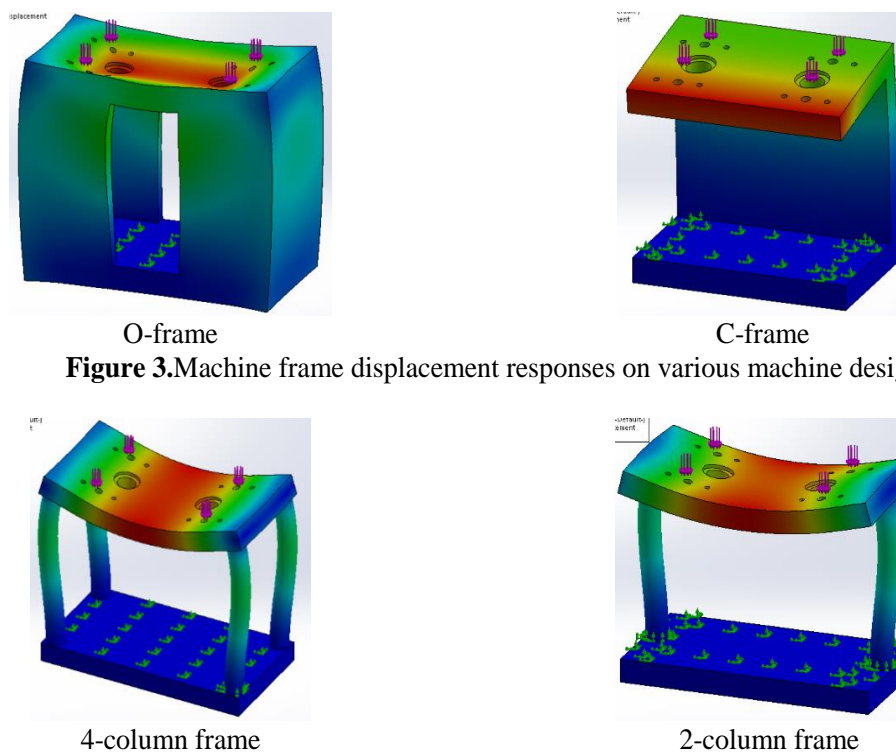
##### 4.1 Machine Frame Displacement Responses on Different Materials

Figure 3 and 4 show the results of deflection of various machine frames on both aluminium alloys 6061 and mild steel. Four points of 200N force were exerted at the machine frame's top surface to simulate the actuation force from the solenoids. The C-frame showed  $0.1362\text{mm}$  and  $0.04721\text{mm}$  of displacement for aluminium alloy 6061 and mild steel respectively. The deflection of this frame design was found larger from the allowable deflection tolerance. Meanwhile, the O-frame structure demonstrated  $1.13\mu\text{m}$  and  $0.3835\mu\text{m}$  of deflection for aluminium alloy 6061 and mild steel respectively. Meanwhile, 4-column frame shows  $12.46\mu\text{m}$  and  $4.19\mu\text{m}$  deflection for aluminium alloy 6061 and mild steel while 2-column frame deflection was found to be at  $17.09\text{mm}$  and  $5.73\text{mm}$  for aluminium alloy 6061 and mild steel respectively. Table 1 summarizes the deflection results for all cases and materials. It can be concluded that the O-frame design produced stiffer structure characteristic for both materials with the least deflection which is still within the desired tolerance. In addition, both 2- and 4-column frames in mild steel materials also demonstrated higher strength and passed the design tolerance specification.

##### 4.2 Upper Die Displacement Responses

Upper die plays an important role during forming process as it is the only moving component to transmit force from the solenoids to the lower die. Three different thicknesses for top and punch guide plates were used; 15, 20 and 25mm. Deflection characteristic of different thickness of top plate on aluminium alloy

6061 and mild steel is shown as in Figure 5. Based on the results, the top plate with 15 mm thickness showed deflection at  $7.20\mu\text{m}$  and  $2.41\mu\text{m}$ , 20mm thick,  $3.27\mu\text{m}$  and  $1.09\mu\text{m}$  for both aluminium alloy 6061 and mild steel respectively. Deflection characteristics for both top and punch holder plate were found to be within the tolerance for both materials. For 25mm thickness of top plate, the results demonstrated  $1.87\mu\text{m}$  and  $0.624\mu\text{m}$  deflection for aluminium alloy 6061 and mild steel respectively. Figure 6 presents deflection characteristic of different thickness of punch holder plate for both materials. The applied force simulates direct contact between the top and punch holder plate during actuation. Based on the results, punch holder plate with 15mm thickness produces  $9.09\mu\text{m}$  and  $3.07\mu\text{m}$ , for 20mm thickness,  $2.47\mu\text{m}$  and  $2.01\mu\text{m}$ , for 25mm,  $0.83\mu\text{m}$  and  $0.59\mu\text{m}$  for aluminium alloy 6061 and mild steel respectively.



**Figure 3.** Machine frame displacement responses on various machine design.

**Figure 4.** Comparison studies of machine frame deflection on aluminium alloy 6061 and mild steel.

Table 2 summarizes the deflection results for both top and punch holder plates. Both plate from mild steel material qualified the simulation evaluation which obey the design tolerance. However, due to good machinability characteristic of the aluminium alloy 6061 compared to the mild steel, this material has an advantage for the consideration. Based on the deflection results, 25mm and 20mm thick was selected for top and punch holder plate respectively.

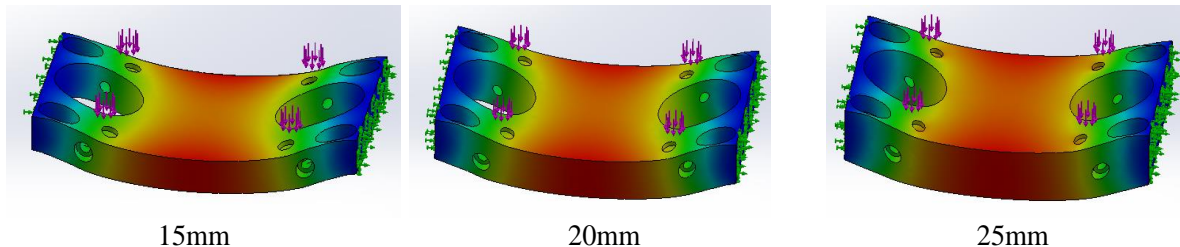
#### 4.3 Die Plate Displacement Responses

Figure 7 shows deflection occurred on the die plate for both materials. There is a part collection drawer/tunnel under the forming die which could weaken the structure. To determine the least deflection to accommodate the location of the part collection drawer, a study of the relationship between different positions of parts collection drawer's hole (denoted as distance  $d$ ) and structure deflection was conducted.

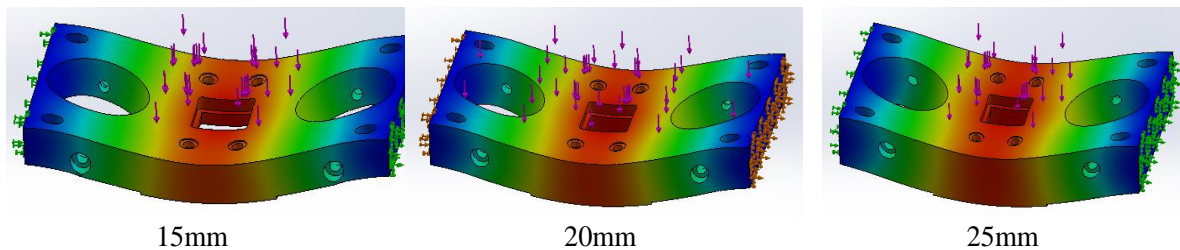
Table 3 summarizes deflection on different drawer's position. The results indicated that the deflection occurred on both materials structure met the design tolerance. Therefore, changes in distance  $d$  did not contribute to the excess deflection of the machine's structure.

**Table 1.** Summary of machine frame deflection on aluminium alloy 6061 and mild steel.

Machine frame type	Deflection ( $\mu\text{m}$ )	
	Aluminium alloy 6061	Mild steel
C-type	136.20	47.20
O- type	1.13	0.38
4-column type	12.46	4.19
2-column type	17.09	5.73



**Figure 5.** Comparison studies of top die deflection on both materials for different thickness

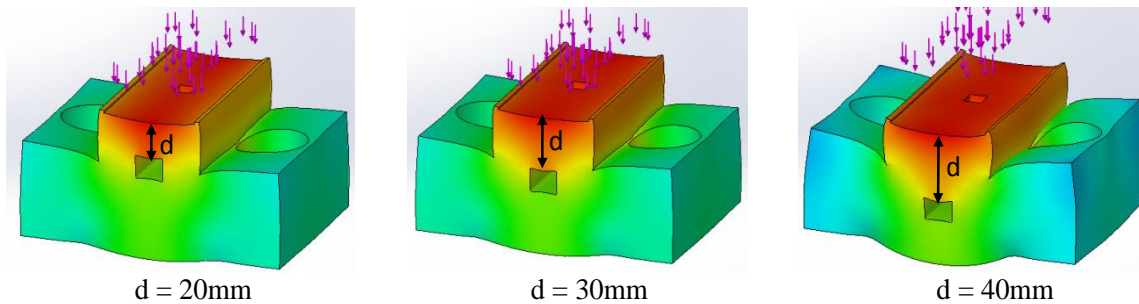


**Figure 6.** Comparison studies of punch holder plate deflection on both materials.

**Table 2.** Deflection of the upper die components

Upper die components	Thickness (mm)	Deflection ( $\mu\text{m}$ )	
		Aluminium alloy 6061	Mild steel
Top plate	15	7.20	2.41
	20	3.27	1.09
	25	18.69	6.24
Punch holder plate	15	9.09	3.07
	20	2.47	2.01
	25	8.33	0.59





**Figure 7.** Comparison studies of a die plate deflection at different  $d$  distance.

**Table 3.** Summary of deflection for different drawer distance  $d$  from the top surface.

Drawer distance, $d$ from top surface	Deflection ( $\mu\text{m}$ )	
	Aluminium alloy 6061	Mild steel
20	3.241	0.109
30	0.311	0.104
40	0.245	0.101

## 5. Conclusion

A design concept of a low energy machine system for a micro-sheet-forming was made based on the lowest sturdy O-frame type. Solenoids were used as a mean of actuation. Maximum deflection around was found to be between 2-3  $\mu\text{m}$  by using aluminium alloy 6061 with 25mm and 20mm thick on top and punch holder plate structures respectively.

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