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Simulation of Forming Process as an Educational Tool Using Physical Modeling

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Abstract

Metal forming process simulation requires a very high cost including the cost for dies, machine and material and tight process control since the process involve very huge pressure. A physical modeling technique is developed and initiates a new era of educational tool of simulating the process effectively. Several publications and findings have shown a potential of the techniques else where. The objective of the paper is to simulate the closed-die forging. In this work, billet material from plasticine is used and dies are fabricated from perspex. The result indicates that billet volume and geometry of the billet is significant in forming process to measure the filling-ability and forming load required in the process.

Keywords: Similarity analysis, Physical modeling, Forming, Educational tool

1. Introduction

Forming can be described as a process in which a piece of metal is shaped to the desired form by plastic deformation starting form such as bar, billet, bloom or ingot (Vasquez et al., 1996). Generally there are two types of forming, sheet metal forming or bulk forming and it can be categorized as hot or cold forming. Initially forging operation has various advantages compared to other metal manufacturing including little loss of material, improved strength, geometrical precision of components and high production rates. Currently, forming process design (mainly die) is carries out trial and error based on intuition and experience of the skilled designer who is familiar with the process. In forging process, performance of the die is measure based on quality of the forged parts and reliability of the die itself.

The methods of studying forming processes can be categorized as the analytical, numerical and experimental methods (Vasquez and Altan, 2000). Experimental requires high capital cost in terms of equipments i.e. die and machine and material, therefore to save cost physical modeling is employed. In most cases numerical methods provide more flexibility than physical modeling since they allow for quick changes in the tooling design but the student cannot understand the process effectively since it does not provide definitive response about the process. The similarity law proposed by Powelski (1992) is utilized to initiate the physical modeling technique and extend by several researchers e.g. Navarrete et al. (2001), who derived the dimensional analysis of closed-die forging to study the stress distribution of the die. The use of physical modeling can reduce load and energy required, reduce the size of forming machine, simple experimental procedure, easy observation of the flow pattern and cheap and requires easier methods for material and die preparation. Plasticine is the most widely used model material because of low price, easily found and non-toxic, other material such as lead, tin and wax also being used (Vasquez et al., 1996). For die material, wood, perspex or aluminum is the most often use.

Many researchers have been conducted and among the recent finding are by Pertence and Cetlin, (2000), who simulate the cracking behavior by focusing on ductility of the material. Yuli et al., (2000) used the physical modeling to perform the forging process of grade 2 stator blade. Zhan et al., (2001) extend the study by using plasticine as a billet material and equipped by platform as a damper to produce the same shape. Sofuoglu and Rasty (2000) study the flow behavior of the plasticine by taking into consideration color of the plasticine, lubrication and deformation speed. He found that they had a significant affect. Fereshten-Saniee et al., (2004) study the frictional behavior of bulk metal forming process and in their research thirteen different lubricants and conditions were employed and result shows that physical modeling can effectively model almost all of the friction conditions. Fereshten-Saniee and Hossein (2006) investigate the effect of flash allowance and bar size on forming load and metal flow and indicate that the greater flash allowance, the larger the forming load. They also studied the effect of axisymmetry of part and found out that part with horizontal axis much sensitive to forming load compared to vertical. Moon and Tyne (2000) used the physical modeling as a validation tools to investigate the cracking criteria resulting from upper bound technique.

Utilization of physical modeling in simulating the manufacturing process for teaching purpose is still less and one of the example is done by Button (2000) and he found that the physical modeling also can be as an effective educational tool and integrate the numerical simulation to compare with the experimental result. Similarly Kridli and Orady (2003) perform the hydro-forming process and effectively introduced to the student.

The paper intent to demonstrate the die filling performance of forming process and a case study of universal joint is illustrated to simulate the process. Here several design parameters will be studied such as billet weight and shape of the die and the filling-ability and forming load is observed at each parameter and use as a performance indicators. The paper is organized as follows; begins with an introduction, and then theoretical background of the forming process and similarity law is briefly explained. After that the process of CAD/CAM of the dies is present, followed by physical modeling procedure. Next the result is discussed and paper ends with conclusion.

2. Similarity Law

2.1 Theoretical Background

There are two parameter used in evaluating the forging process i.e. forming load and die filling capability. Based on simplified SLAB method, for closed-die forging process the forming load can be expressed as below (Altan et al., 2005);

$$P_{ca} = 2\pi r^2 \left(\frac{m}{\sqrt{3}} \frac{\sigma_c}{3} \frac{r}{H} + \frac{\sigma_{ea}}{2} \right) \quad (1)$$

Where

H = cavity height

r = radius or half width of the cavity

t = thickness of the flash

w = flash width

σ_f = flow stress in the flash region

σ_c = flow stress in the cavity

m = frictional shear factor

σ_{ea} = stress at the entrance from the cavity to the flash of an axisymmetric cross section

As the process is considered as flashless, so that stress at the entrance of flash, σ_{ea} equal to zero and the forming load becomes;

$$P_{ca} = 2\pi r^2 \left(\frac{m}{\sqrt{3}} \frac{\sigma_c}{3} \frac{r}{H} \right) \quad (2)$$

And for die filling analysis, the capability is measured based on viscosity of the semi-solid material and friction effect since the forming process involve the metal being pressed to the plasticity stage before it can deform. Kang et al., (1998) study the filling pattern of semi-solid aluminum die shape play important role in filling efficiency. To express the theory, Okano proposed the relationship using the below equation (Okano, 1994);

$$\eta_a = \eta_{La} \left(1 + \frac{\alpha \rho_m C^{1/3\dot{\gamma}-4/3}}{2\left(\frac{1}{f_s} - \frac{1}{0.72 - \beta C^{1/3\dot{\gamma}-1/3}} \right)} \right) (0.72 - \beta C^{1/3\dot{\gamma}-1/3} \rangle f_s) , \alpha = 2.03x10^2 \left(\frac{X}{100} \right)^{1/3} , \beta = 19.0 \left(\frac{X}{100} \right)^{1/3} \quad (3)$$

Where

η_a = Apparent viscosity of semi-solid material

η_{La} = Apparent viscosity of molten metal

C = Solidification rate

ρ_m = Density of molten metal

$\dot{\gamma}$ = Shear rate

f_s = Solid fraction

X = Solute percentage of binary alloy

The friction model for 2D process is proposed by Levanov et al. (1976) can be shown as follows;

$$\frac{\tau}{k} = m\left(1 - \exp\left(-1.25\left(\frac{q}{\sigma_0}\right)\right)\right) \tag{4}$$

Where

m = Friction factor

q = Contact pressure

σ_0 = Equivalent yield stress

2.2 Similarity Analysis

Similarity law developed by Powelski (1992) is used to simplify the processes that usually involve many parameters. Initially analysis demands expensive and time-consuming experiment and difficult mathematical calculation. The theory of similarity can be explained by using the following theorem;

Theorem 1: For two similar processes all similarity numbers are equal in pairs

Theorem 2: The similarity numbers are connected in similarity equations, which are dimensionless solutions of the regarded problems and are valid for all similar processes.

Theorem 3: For the similarity of two processes it is necessary and adequate that they are of the same qualitative kind and that their defining similarity numbers are equal in pairs.

From the above equation, forming load is a function of cavity height, *H*, radius or half width of the cavity, *r*, thickness of the flash, *t*, flash width, *w*, flow stress in the cavity, σ_c and frictional shear factor, *m*. After performing the dimensional analysis, two similarity number have been identified, but the most related and of special interest is $\Pi = \frac{H}{r}$, which related to the effect of the geometry and size of the die to the load required in the process whereas for die filling pattern is a function of apparent viscosity of molten metal η_{La}, solidification rate, C, density of molten metal, ρ_m, shear rate, $\dot{\gamma}$, solid fraction, f_s solute percentage of binary alloy, X and friction phenomenon. As a result three similarity numbers have been identified but the most relevant is $\Pi = \frac{A_r}{A_a}$, which shows the same effect to the previous case and for conclusion, from the analysis of both two performance indicators, the most significant factor is the dimension or shape of the part or here consider as weight of the billet material.

3. Methodology

The simulation process can be described as follows;

3.1 CAD/CAM of the Die

Starts with development of CAD model of the die and here SolidWorks software is used. Followed by die fabrication using CNC milling machine is as shown in Figure 1 to 3. Physical modeling is conduct after billets are prepared.

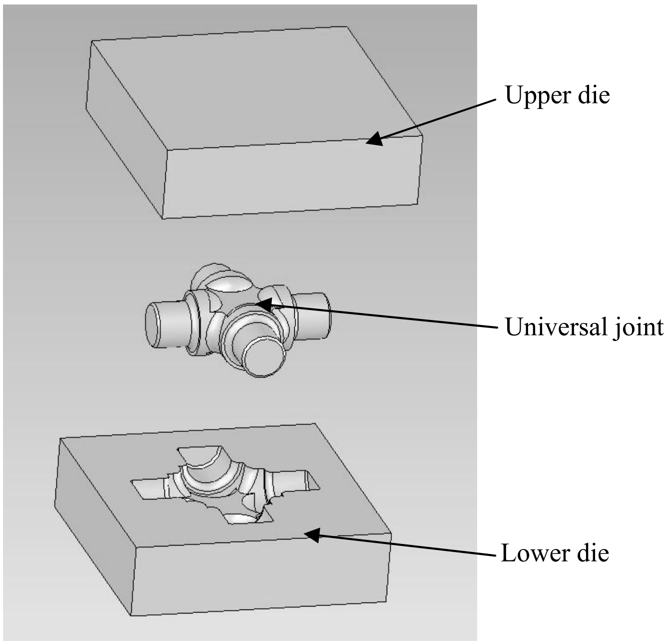


Figure1. CAD model of the upper and lower die

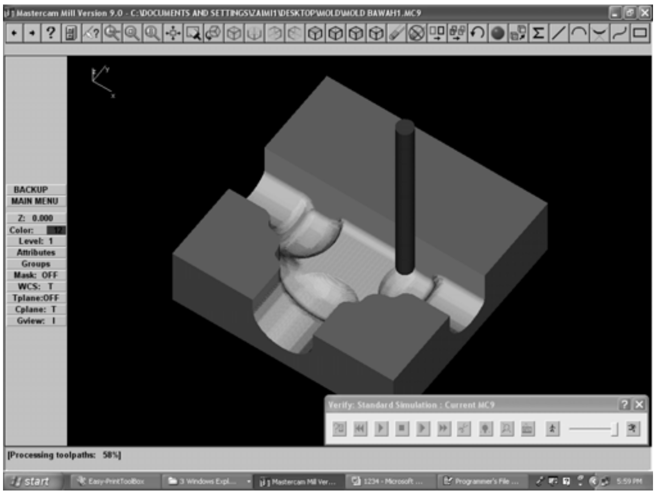


Figure 2. CAM simulation using MasterCAM

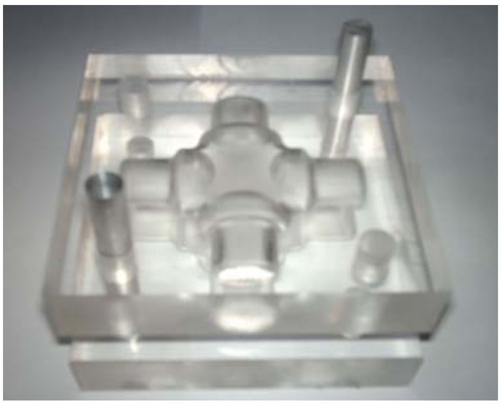


Figure 3. Fabricated lower and upper dies with guide pin

3.2 Preparation of the Billet

In preparing the billet, the reference weight is determine manually by compressing the plasticine into the die and weighted after de-flashing. As a result a billet of 146.20 grams is obtained. To get the exact weight of the billet, a physical modeling is performed and weights of the billets are varied. Figure 4 shows the different size of billet represent different weight of the billet. Here the weight of the billet used rather than volume due to difficulty of getting density of the plasticine.

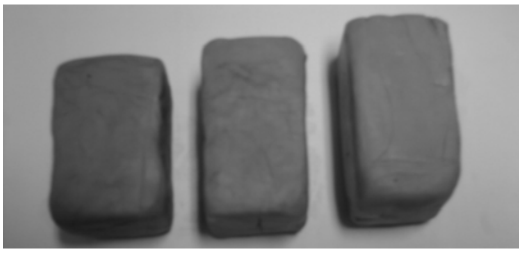


Figure 4. Different size and color of billet

3.3 Physical Modeling

The physical modeling flow process is as shown in Figure 5. After the billet is prepared, it is then locate in the middle of lower and upper dies. The compression begins, after the height of the deformation or stroke as shown in Figure 5 is measured. In order to avid material from stuck inside the die, a glycerin is used. Besides that it also acts as lubricant. The weight of the billet is measured before and after forming and final weight of the part is determined after de-flashing.

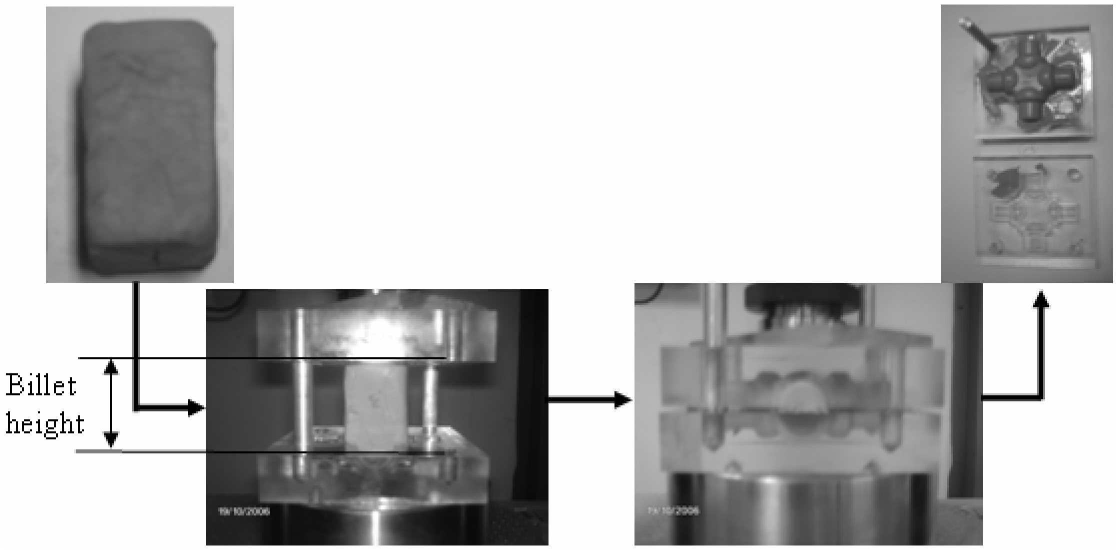


Figure 5. Physical modeling flow process

4. Density Determination

Plasticine is a non-homogenous material, so that properties is varies from different manufacturer. Before the forming process is begin, density of the plasticine need to be determined. The value is obtained based on Archimedes Theorem. The result of different water level is determined and before and after experiments, samples are weighted. The density determined will be used to calculate the actual weight of the part, so that it can be compared with result from experimental. For this case four sets of samples is prepared and it can be divided into two, compress and non-compress plasticine:

i) For uncompressed plasticine, there are three types of samples:

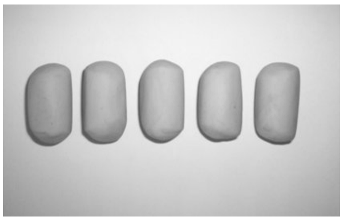
Sample #1 – a sample of same weight and repeated for five times, sample is shown in Figure 6 (a)

Sample # 2 – five samples in same weight and same shape, samples shown in Figure 6 (b).

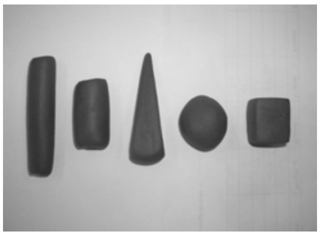
Sample # 3 –five samples almost same weight at varied shape as shown in Figure 6 (c).

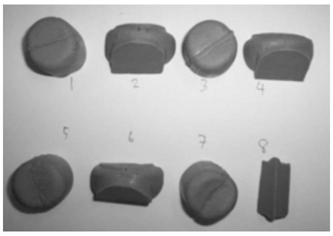
ii) For compressed plasticine,

Sample # 4 – eight samples in varied weight and shape as shown in Figure 6 (d)



(a) Sample #1 (b) Sample #2





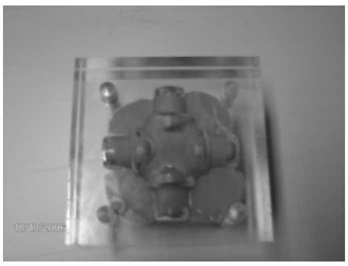
(c) Sample #3 (d) Sample #4

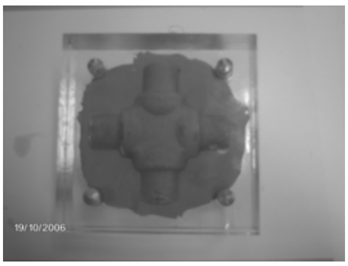
Figure 6. Four sets of samples for density determination

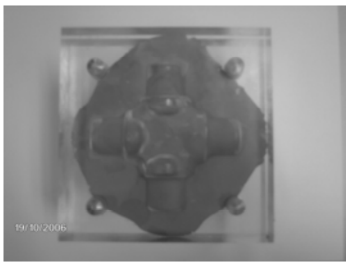
From CAD data the volume is of case study i.e. universal joint is 74569.777 mm^3. From here the density of each sample is obtained. Since the plasticine used in the physical modeling is compressed during compression process, the density used is 1888.70 kg/m^3.

5. Result and Discussion

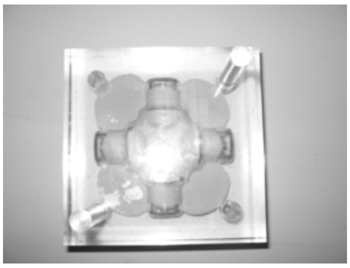
The experiment is conducted to study the capability of material to fully fill the internal cavity of the die, especially the chamfer and fillet at the end of the part. The result can be divided into three main areas i.e. the effect of billet weight, percentage of un-filled die and forming load. The physical modeling is conducted at varied billet weight. Sample #2 to #6 depicts the weight increment by 10% and Sample #7 to #9 represent weight reduction also by 10% of the reference weight. To get the reference weight, a manual compression test is conduct and the maximum weight of plasticine can be filled in the dies is 146.20 grams. The deformed billet after compression using Universal Testing Machine is as shown in Figure 7. From the experiments, the maximum billet can be fillet in the dies is 153.70 grams (Figure 8) and this amount is assumed as fully filled part and used as reference to calculate filling-ability. From the distribution pattern of the material, shows quite similar pattern and this is proved that un-balance compression is not crucial.

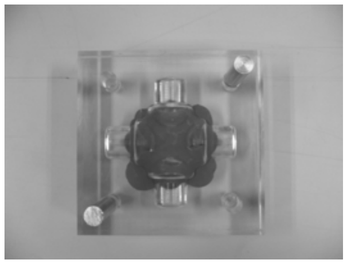






(Sample #1) (Sample #2) (Sample #3)





(Sample #7) (Sample #8) (Sample #9)

Figure 7. Deformed billet before de-flashing

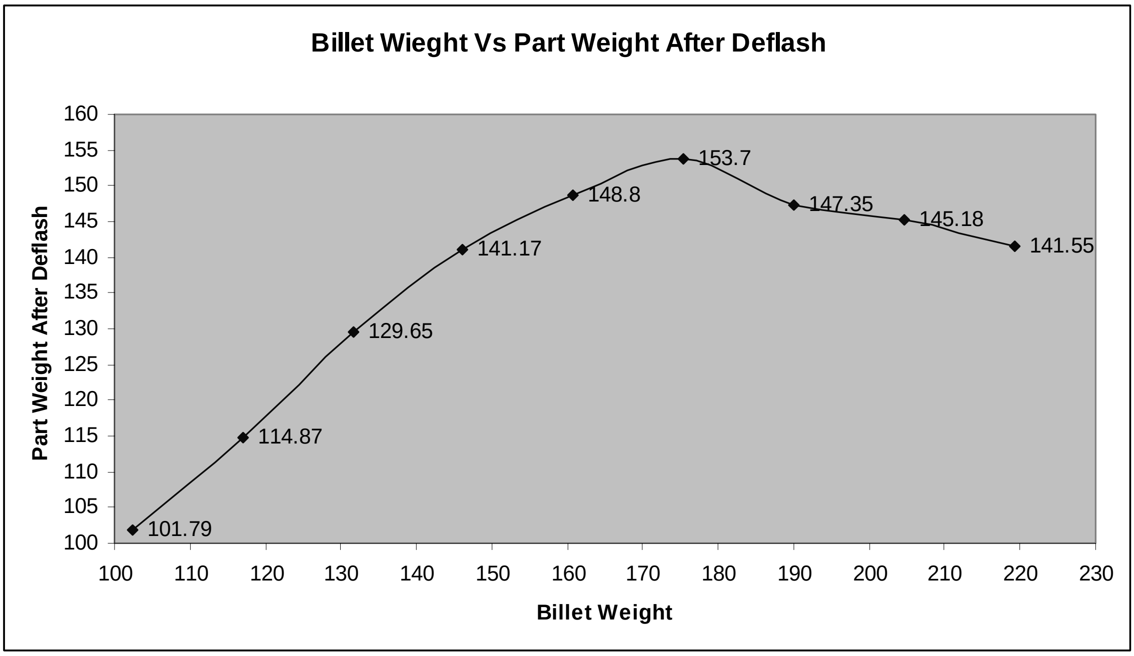


Figure 8. Determination of maximum part weight

5.1 Die Filling

From the above result, shown that Sample #3 shows the highest part weight and here it is assumed that this the maximum weight of part or 100% filled die. The un-filling weight is determined by comparing the maximum filled part to the measured part from the experiment and the result is summarized in Table 2.

Table 2. Data for un-filling die

# Sample	Part Weight in grams after de-flashing	Un-filling Die in grams	Un-filling Die in %
1	141.07	-11.92	7.79
2	148.66	-4.33	2.83
3	152.99	0	0
4	147.15	-5.84	3.82
5	145.14	-7.85	5.13
6	141.22	-11.77	7.69
7	129.50	-23.49	15.35
8	114.65	-38.34	25.06
9	101.71	-51.28	33.52

The negative value in the Table 2 means there are sections of the die that material cannot be reached due to complicated shape or too small. For the example, the die filling percentage of Sample #2 is where only about 3% unfilled is observed, while for Sample #9 about 34% unfilled is recoded. Although both of them cannot fulfill the die, but the increase of billet weight give the better die filling.

5.2 Forming Load

Figure 9 below shows the summary of the result of the load required for each samples. Compare Sample #1 with Sample #6 which has 50 percent more in height than Sample #1, the maximum load shows a similar value which is about 0.75 kN. This mean that relatively when the billet weight increases the higher load is need to complete the forming process. The result also indicates that, the shape or geometry of the billet also affect the load. The effect of billet height and weight is shown in the load-displacement curve (Figure 9). It can be seen that for sample billet with higher in weight, a greater force is needed to form the billet to desired form compare with the sample with lower weight. This could be due to higher contact surface between billet material and die which cause greater friction force and, consequently, larger forming load.

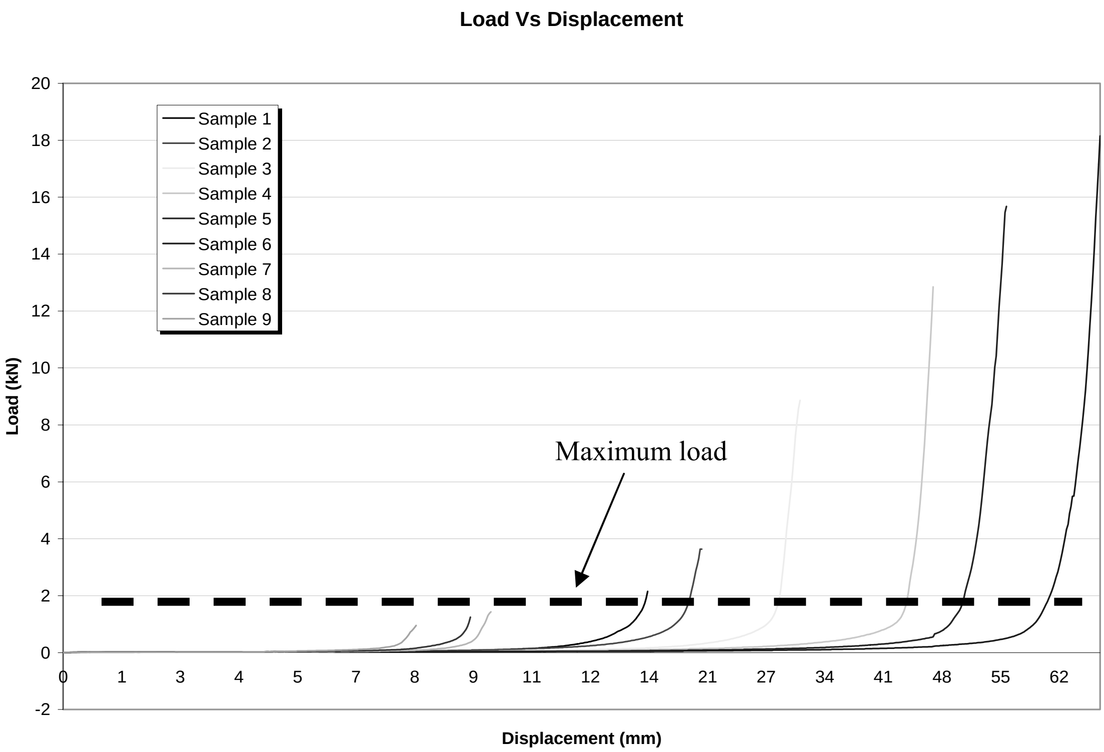


Figure 9. Load-displacement (billet height) curve

6. Conclusion and Future Works

The paper presents the exploration of a new approach to enhance the conventional teaching method by utilizing the physical modeling in simulating the forming process. In the simulation, the effect of billet weight to the die filling and forming load of forming process by using physical modeling. By using trial-error method, the exact volume of the part weight is determined and used to use as a reference to obtain the un-filling volume. Here since the density of the plasticine is varied depends on manufacturer and the other factors such as environment and process condition, a simple experimental had been performed to determine the density of the plasticine. The result indicates that the weight of the billet will greatly affect the die filling and forming load. For future research, the die filling performance will be study from the perspective of die geometry in terms of fillet, corner radii and size of part. The utilization of physical modeling prove will helpful in determining the performance of forming process, but due to limitation many factors are not taken into consideration such as stress distribution and effect of lubricant to the process.

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