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Review Article

Teaching Metal Forming using Plasticine and Additive Manufactured Tools

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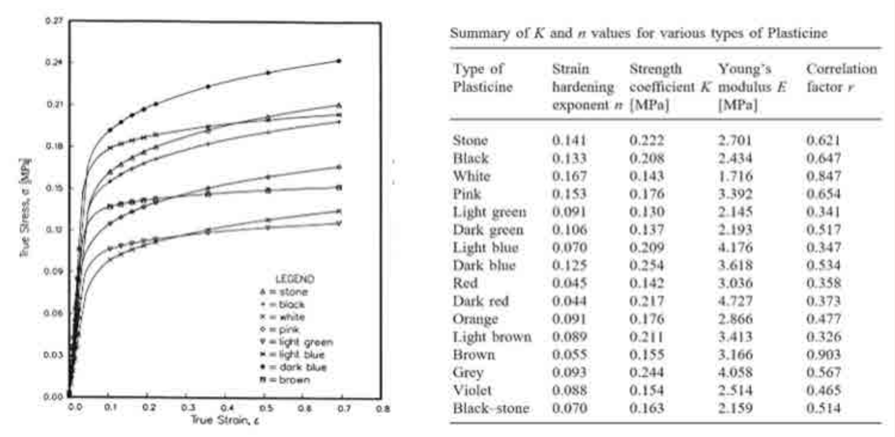
Abstract

Metal forming is a pivotal teaching subject owing to its extensive use in automotive, aviation, energy, military, and other metal industries. An effective educational method for studying key principles in metal forming theory is hands-on learning rather than traditional classroom teaching. At Ben-Gurion University, a unique laboratory was established to promote the teaching of a metal forming curriculum. In this laboratory, metal forming processes were illustrated and practiced using Plasticine as a metal substance formed by "3D printed", additive manufactured (AM) nylon tools. Vaseline was the prime lubricant used to demonstrate the influence of friction on metalwork. Metal forming operation forces were directly measured using a weight scale. The strain distribution of different forming processes was evaluated by measuring the change in the thickness of colored Plasticine layers across the workpiece in comparison to numerical simulation results. Students discovered correlations between the calculated forces according to classic empirical equations and the actual measurements that evidenced the influence of friction. It was found that students who participated in "metal" forming in the laboratory using Plasticine not only had a more comprehensive understanding of metal forming processes, but they also had more confidence in the theory as it was learned in class.

Introduction

Plasticine, wax, clay and lead have been used as physical modeling materials for metal forming processes for more than 50 years. Model materials appeared to simulate metal flow and attain a relatively accurate quantitative estimation of forming forces regarding the influence of deformation and friction. Plasticine forward- and backward-extrusion forming forces were evaluated by *T. Altan et al.* [1] in 1968 and concurred with industrial extrusions [1]. A mixture of 70% Plasticine and 30% Chalk was used to investigate the influence of die profile on strain distribution and to determine "metal" flow patterns for different die configurations by [2]. Maximum extrusion forces Vs. die-opening geometry (different die pocket sizes) were assessed with an accurate measuring device. The use of a commercial FEM code FORGE3® to study the influence of the distribution of multiple die holes on extrusion parameters was reported by [3]. Plasticine has been used in experiments of material flow in multi-hole extrusion and, for comparison, in experiments of metal extrusions. The metal flow pattern, extrusion pressure requirements, and temperature profile were established and concurred with experimental results shown using FEM simulations. Plasticine was used as a physical model to evaluate both metal flow and metal forming foreseen in closed die forging operations [4]. It was emphasized that the influence of friction was difficult to simulate since, in the industry, friction is significantly influenced by temperature, while the friction between Plasticine and dies is dominated by lubricant. The development of forging pass schedule algorithms is typically achieved by calculating the optimum number of passes and the reduction in each forging operation in order to economize power and minimize forging cycle time. A comprehensive optimization of forging passes using Plasticine as a physical modeling material was done [5]. Flash allowance is a major issue for closed die forging owing to the large forging forces needed for the metal flow at elevated temperature through gutter clearance. Pass schedule algorithms for hot closed die forging were developed using Plasticine specifically to characterize and optimize metal flow during the flash creation of complex axisymmetric forgings [6]. A 600kN Instron tensile test machine was used to measure the forming forces of the closed die forging operation. A ring forging test was performed to determine the friction coefficient of Plasticine using lubricant. A ring compression test was also performed to determine the friction coefficient of Plasticine in modeling experiments by [7]. Measured values were used to calibrate the ring compression test at different temperatures using CAMPform© numerical simulations. CAMPform© calibration curves for Plasticine were presented. The friction coefficient of Plasticine was evaluated using ring compression tests that utilized 16 different lubricants [8].



Summary of K and n values for various types of Plasticine

Type of Plasticine	Strain hardening exponent n	Strength coefficient K [MPa]	Young's modulus E [MPa]	Correlation factor r
Stone	0.141	0.222	2.701	0.621
Black	0.133	0.208	2.434	0.647
White	0.167	0.143	1.716	0.847
Pink	0.153	0.176	3.392	0.654
Light green	0.091	0.130	2.145	0.341
Dark green	0.106	0.137	2.193	0.517
Light blue	0.070	0.209	4.176	0.347
Dark blue	0.125	0.254	3.618	0.534
Red	0.045	0.142	3.036	0.358
Dark red	0.044	0.217	4.727	0.373
Orange	0.091	0.176	2.866	0.477
Light brown	0.089	0.211	3.413	0.326
Brown	0.055	0.155	3.166	0.903
Grey	0.093	0.244	4.058	0.567
Violet	0.088	0.154	2.514	0.465
Black-stone	0.070	0.163	2.159	0.514

Figure 1: Mechanical properties of Plasticine [11].

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Several interfacial conditions were conducted at intermediate strain rates using a laboratory model-forging hammer. Calibration curves for the f factor from the ring tests with Plasticine specimens and the model hammer were elucidated. The friction and behavior of Plasticine in different colors was also investigated [9,10]. Since Plasticine is made in different colors, for many years it was widely used to measure strain distribution in metal flow processes using thin colored layers. It now appears, however, that the mechanical property of Plasticine is significantly influenced by the colors due to the presence of color additives. The mechanical properties of 16 different colors of Plasticine were evaluated using compression tests where the flow behavior was determined (Figure 1) [11].

At room temperature, Plasticine proved to be an accurate physical modeling material to simulate the strain distribution and deformation behavior of hot rolling processes of steel above 1000 ºC. Compression tests were carried out at numerous velocities using a universal testing machine, characterizing the stress-strain relation of Plasticine. The influence of temperature and time, the age hardening effect, and the strain rate sensitivity of Plasticine were established [12]. Metal forming is a pivotal teaching subject owing to its direct implications for the automotive, aviation, energy, military, and other metal industries. The best way to teach key principles in metal forming training is by traditional hands-on learning rather than classroom presentation or teaching by computer simulation. In 1971 in his book "Metal Forming", Avitzur demonstrated the potential of Plasticine as a research and educational tool [13]. Plasticine, he added, could be formed into precise shapes using low forming forces. Furthermore, he stated that the forming of Plasticine was a low-cost process since it could be molded over and over again, the cost of dies could be reduced using Aluminum and wood dies, and there was no need to heat up either material or dies to an elevated temperature. Since physical modeling with Plasticine was done using low forming forces, no expensive high force presses were needed and experiments could be done using everyday lab equipment. *S. Tonini* [14] reaffirmed that the difficulty of teaching metal forming to undergraduate students of mechanical engineering departments lay in the complexity of teaching hot forging of complex forging dies, high capacity presses, and forging metals at elevated temperatures [14]. Moreover, numerical simulation did not provide a definitive response about the process given the uncertainties of plastic behavior in deformed material and under tribological conditions. The use of Plasticine as a model material for closed die forging teaching was decidedly effective due to low cost, good plastic flow, and accurate modeling of the forging forces. The forging of the steel crankshaft was mimicked by Plasticine using synthetic resin dies that used many colored layers of Plasticine, thus enabling the observation of material flow and strain distribution in the forgings. It was concluded that the use of Plasticine as a physical model material was an interesting and inexpensive way in which to improve the quality of the practical education of undergraduate students. A. B. Abdullah determined the similarity laws for Plasticine forging [15]. He phrased equations for forging forces regarding viscosity, referring to T. Altan's work [1]. During the forging experiments, they measured the density of Plasticine billets before and after forging operations. They analyzed the flash of the excess material out of the die, optimized the forging forces, and concluded that the use of Plasticine enhanced the conventional teaching method by utilizing physical modeling in simulating the forming process.

At Ben-Gurion University, a unique laboratory was established to promote the teaching of a metal forming curriculum. In this laboratory, metal forming processes were illustrated and practiced using Plasticine as a physical metal substance formed by "3D printed", additive manufactured (AM) nylon tools. Vaseline was used as the prime lubricant to demonstrate the influence of friction in metalwork. The metal forming operation forces were directly measured using a weight scale. Students discovered correlations between the calculated forces according to classic empirical equations and the actual measured forces that evidenced the influence of friction. The strain distributions of different forming processes were evaluated using thin layers of color Plasticine. The strain distribution was evaluated by measuring the change in thickness of the colored layers across the workpiece. Students evaluated strain distribution according to tools geometries and friction compared to the numerical simulations of those processes. The influence of friction on forming processes forces was measured directly and compared to the theoretical forces that were calculated. It was observed that students who participated in "metal" forming in the laboratory using Plasticine not only had a more comprehensive understanding of metal forming processes, but they also had more confidence in the theory as it was learned in class.

1. Experimental

Plasticine was recognized as a superior physical model material for many reasons: it could be used repeatedly through remodeling, it could be formed into any shape of specimen, and it had a strain hardening effect and a strain rate sensitivity at room temperature, except for very low strain rates. Plasticine was made in different colors and thus could be easily formed into layers enabling it to acquire internal strain distribution. It appeared that the mechanical properties were quite different for different colors and influenced by temperature. Since Plasticine had very low flow stress at room temperature, it could be formed using inexpensive tooling and presses. One of the disadvantages of Plasticine was that the flow stress varied significantly from batch to batch and prior to using it, it required kneading in a preforming operation to eliminate air pockets. Most notably, the flow stress and deformation behavior of Plasticine followed common-use metal forming equations. At room temperature, Plasticine behaved similarly to Aluminum alloys at 400ºC and steel alloys at 1000 ºC, the most relevant forming temperature at recrystallization temperatures (0.6Tm). The tools and dies were made from Nylon 12 of EOS-PA2200 by a powder bed laser additive manufacturing (AM) technique using a P760 machine. Nylon (a.k.a. polyamide) is a popular material in the plastics industry known for its toughness and flexibility. AM of Nylon typically requires temperatures near 250 ºC. The advantages of nylon as a material for tools and dies were that it was tough and partially flexible, high-impact resistant, and had good abrasion resistance with low friction. Tools and dies were designed to be used in class with hands applying force as well as simple measuring devices such as home weight scales, luggage scales, rulers, and cellphone cameras. Vaseline was used as a lubricant to reduce friction. In some cases, students voluntarily built devices to improve the parallelism of the dies (as in upsetting experiments). In other cases, students proved creativity in their use of colors and experimental setups to gain more information from the work itself. Students were divided into groups of three and as a part of the Plasticine lab, they submitted lab reports that included theoretical descriptions, a literature survey of the processes they were about to explore, calculations of the forces and other parameters of the metal forming process (using Plasticine mechanical properties and friction from literature), and detailed experiment plans.

1.1. Extrusion experiments

A 60ml medical injector with a 29mm internal diameter that can be bought in any pharmacy was used as the extruder device (Figure 2). Various 3D printed dies were used to demonstrate the influence of die parameters on the extrusion process. 3D printed nylon dies with 7 to 14mm diameter openings (17 to 4 extrusion ratios, accordingly) can be seen in (Figure 2a). Dies with a variety of die angle, and bearing length, along with some multi-pass extrusion dies were used. Rectangular flats and hexagonal dies of differing dimensions were printed to emphasize some of the extrusion parameters (Figure 2b). More complex dies such as bridge die tube extrusion and mandrel tube extrusion were also used. Nowadays, students can design and print their own dies and instantly evaluate the effects of new approaches on the extrusion process.

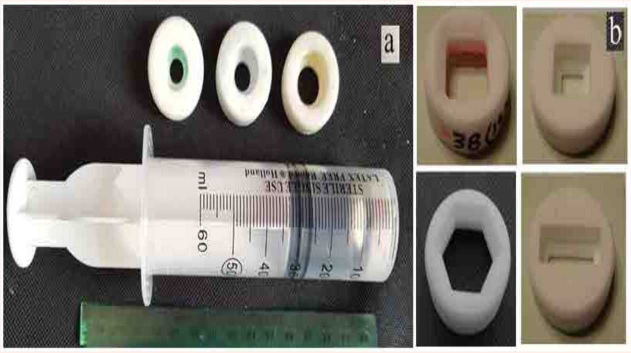

Figure 2: (a) Medical injector serves as an extruder (b) Variety of Nylon 3D printed extrusion dies.

Extrusion process experiments were carried out in the classroom using a weight scale and a ruler to measure extrusion forces and displacement (Figure 3). A video was taken for each extrusion operation, simultaneously showing the force reading and the displacement in order to analyze the extrusion graph with reasonable accuracy. In some cases, students used a color-layered billet (Figure 3) to evaluate the "metal" flow and strain distribution. Interrupted tests were administered to detect the flow from the billet remains to the extruded profile. Samples cut in a cross section with dental floss wire were discovered to be most effective at preserving the layered structure without shearing and blending colors.

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Figure 3: Bridge die tube extrusion experiment setup.

Extrusion dies were printed to emphasize the influence of different parameters in the extrusion empiric equation (Equation 1). The dominant parameter was the extrusion ratio R that expressed the relationship between the initial billet area and the final extruded profile cross section area. In some cases, such as the multi pass extrusion die where the profile cross section area was multiplied by the number of openings in the die, the extrusion ratio decreased, and the extrusion forces were reduced accordingly, as demonstrated to students using dies (Figure 4).

Extrusion Force [Kg]

Average Flow stress $\left[\frac{Kg}{mm^2}\right]$

Friction coefficient

Average Flow stress $\left[\frac{Kg}{mm^2}\right]$

$$P = A_0\bar{\sigma}_{ave}\left[lnR + \frac{2}{3}\alpha + \frac{2lnR\mu}{sin2\alpha}\right] + \pi DL\bar{\sigma}_0\mu$$

Billet Cross section

Reduction $R = \frac{A_0}{A_f} = \frac{D^2}{d^2}$

Die angle [Radians]

Container diameter

Billet length [mm]

Equation 1: The classic extrusion force equation.

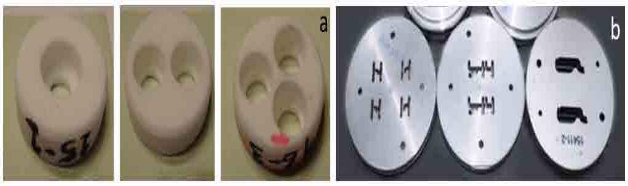

Figure 4: multi pass extrusion dies (a) Nylon 3D printed dies (b) Aluminum extrusion dies [16].

The second most leading extrusion parameter is friction. While in real life, friction is a function of metal couples and temperature, it was critical to demonstrate the influence of friction on both extrusion forces and "metal" flow. Medical grade Vaseline was used to reduce the friction between Plasticine and the plastic "container" and dies. A very small portion of Vaseline was poured on the container and ram (never on the Plasticine billet) resulting in a dramatic decrease of extrusion forces. The third parameter was the die angle (Equation 1), a major influence on "metal" flow and the creation of the Dead Metal Zone (DMZ) in the container corners. Die design and manufacturing are the knowledge and art of extrusion making, and this was an opportunity to demonstrate to students the relationship between work (deformation) and friction within the die. To demonstrate the influence of die angle on the extrusion forces and the "metal" flow pattern, dies with a variety of enter angles were printed (Figure 5a & 5b). Radius-curved dies were also printed (Figure 5c) not only to challenge students but to emphasize the influence of die angle and friction.

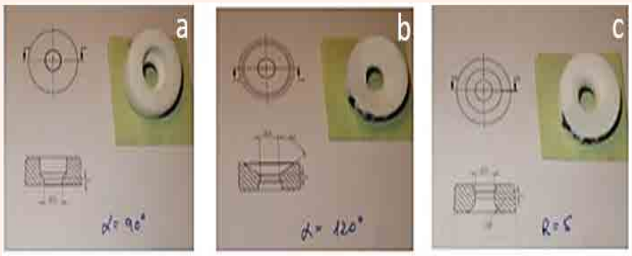

Figure 5: Extrusion dies with vary die entry angle (a) flat die (90°) (b) 120° and (c) R5mm die.

Excluding flow stress and friction, all other extrusion parameters were geometrical factors. The extrusion ratio (R), the die angle (α), and the billet initial diameter and length (D, L) can all be controlled by printing a variety of dies and tools. Tube extrusion can be made using a bridge die where the tube has "seams" characterized by a different microstructure. If the extrusion parameters are incorrect, the mechanical properties of the "kiss-bond" area might be poor (Figure 6). Seamless tube extrusion is made using mandrel tube extrusion technique, easily demonstrated using Plasticine (Figure 7). An Aluminum mandrel was used in order to reduce the friction forces.

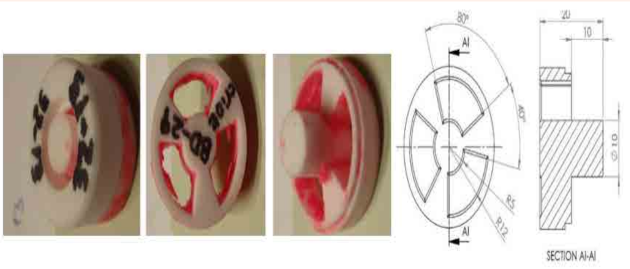

Figure 6: 3D Nylon printed tube extrusion bridge die and drawing.

Diverse mandrel diameters and die dimensions (Figure 7) allowed the extrusion of Plasticine tubes with selected combinations of diameter and wall thickness, representing the influence of extrusion ratio on extrusion forces and "metal" flow. Mandrel tube extrusion was also used to demonstrate an "extrusion cladding" operation while the mandrel was set to be a previously extruded rod of Plasticine with a different color.

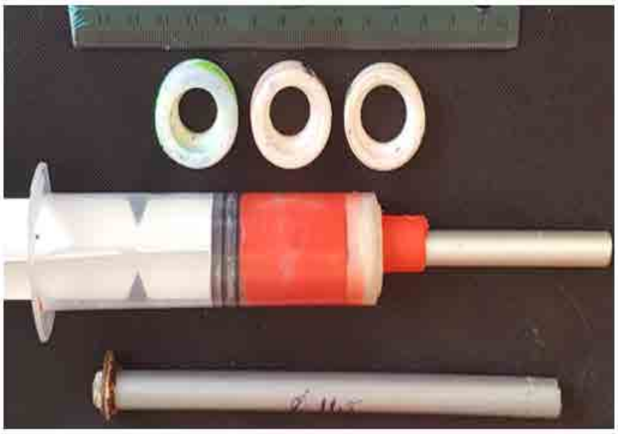

Figure 7: Mandrel tube extrusion setup.

1.2. Backward extrusion

Backward extrusion, sometimes referred to as the impact extrusion process, is an important metal forming process carried out on many scales. From tin toothpaste tubes all the way to Aluminum high pressure diving balloons, multiple products are manufactured using backward extrusion. Although backward extrusion is referred to as an extrusion process and complies with extrusion equations, it is a type of closed die forging process. As with forward extrusion, the dominant parameter is the extrusion ratio R (the relationship between the initial billet area and the final cup cross section area), but in backward extrusion, the die front shape has a major influence on the extrusion forces and metal flow pattern. A backward extrusion set of dies was 3D printed allowing two wall thicknesses (two extrusion ratios) and four different die front shapes (flat to full-hemisphere) as seen in (Figure 8). Concentric alignment rings were added to assure even wall thickness, and an ejector was set in the base to easily eject the final extruded cup. Students used this setup, measuring the forces with a weight scale, while Vaseline was used to reduce friction.

Figure 8: Backward extrusion setup tools.

1.3. Forging of Plasticine

Forging is one of the most common and important uses in the metal forming process, particularly for steel, but also for wrought Titanium and Aluminum alloys manufacturing. Open die forging (as a simple upsetting operation) and cogging (as a main forging operation) are used for the preliminary deformation of cast billets, while closed die forging (as a secondary semifinal manufacturing process) is used to manufacture near net shape (NNS) final products. Both the teaching and the demonstration of forging were challenging in light of the fact that these metal forming operations were done at elevated temperatures using large forging presses in an unsafe environment. For these reasons, Plasticine was used extensively as a physical modeling material for the teaching of forging. In order to teach closed die forging using Plasticine, a set of impression die forging was 3D printed with flash (Figure 9a). Students used color layers to evaluate strain distribution and flow into the gutter. The cogging of Plasticine was done using a variety of corner radius dies. Students used stoppers to set the reduction for each "blow", drawing a mash over the Plasticine face to detect strain distribution. Strain distribution within the billet, as a function of reduction, step size, and rotation (according to cogging plane) was then evaluated (Figure 9b). The folding effect was also evaluated for a variety of corner radiuses, reductions, and step sizes (Figure 9c).

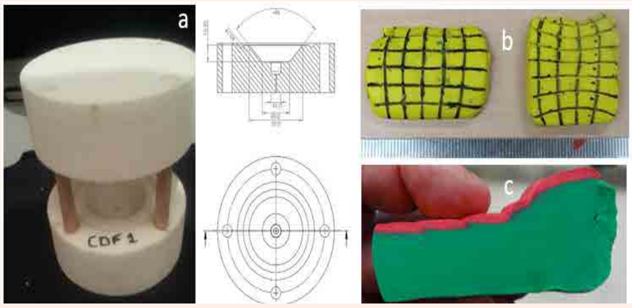

Figure 9: (a) Impression die forging die set. Cogging: (b) strain distribution (c) the "folding" effect.

1.4. Profile rolling

Profile rolling is commonly used around the world to manufacture steel reinforcement bars for concrete. It is also used to manufacture steel H and U-shaped bars for construction and railroad tracks. There is no way to create laboratory-scale profile rolling facilities since the operation takes place at elevated temperatures and the rolling is carried out in many sequential steps. The profile rolling seen in (Figure 10) was designed to allow rolling at a number of different preset reductions (see the stopping pins). The rolling clamping force was applied by hand from above and directly measured by a weight scale that served as the device base. Students used this device both with and without lubrication and they were able to detect the forces needed and the strain distribution using colored layers of Plasticine.

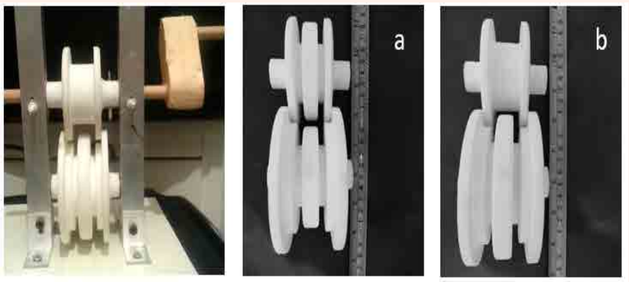

Figure 10: Manual profile rolling machine (a) H shape profile rollers (b) U shape profile rollers.

1.5. Other metal forming processes

Regrettably, the length of this paper prohibits the inclusion of other metal forming processes simulated by Plasticine as a physical model material. A miniature rolling machine was used to roll sheets of colored layered Plasticine in various reductions, demonstrating the influence of reduction on strain distribution and clamping forces. A miniature ring rolling machine was also used for the same purpose. Billet piercing operations also used Plasticine in the preparation of the ring rolling billet, and punching of Plasticine comprising different shapes and cutting blade dies were produced. Heading, both an interesting and common metal forming process, uses forging to manufacture bolts and rivet heads in one step using the local induction heating of a steel bar. Students accurately simulated heading with the use of Plasticine, and they evaluated the friction coefficient between Plasticine and various dies such as metal, polymers, and wood with a ring compression test.

2. Results

2.1. The influence of extrusion ratio

Extrusion ratio is the most effective factor on extrusion forces and metal flow (Equation 1). The students' experiments using dies (Figure 2b) revealed the dramatic influence of extrusion ratio (R) on force. Nevertheless, the use of Vaseline as a lubricant demonstrated force decrease due to the decrease of friction. (Figure 11a) shows the influence of extrusion ratio on force, as published by *Altan* [1], compared to the students' Plasticine extrusion results (Figure 11b) along with measurements Vs. calculations both with and without the use of lubrication for R= 4, 5.5 and 10.

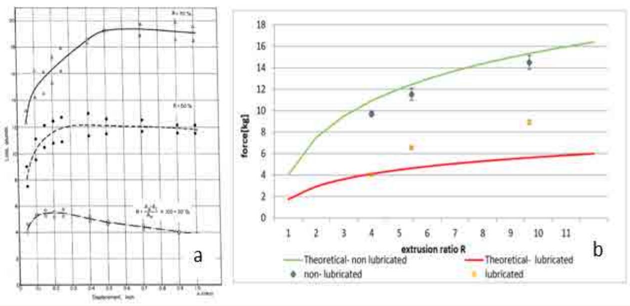

Figure 11: Extrusion ration Vs. extrusion forces (a) load Vs. R [1] (b) students results.

A comparison of experimental Plasticine extrusion forces to Aluminum extrusions [17] can be seen in (Figure 12). The influence of die angle on extrusion forces acts the same, with a minimum at 90º. Additionally, the Plasticine graph displays the influence of lubrication, since instead of 60º, a round R5mm die was used. The graph does not climb as expected, but the influence of lubrication is noticeable as the surface area of round radiuses is high, and the friction forces are higher due to the extensive die surface.

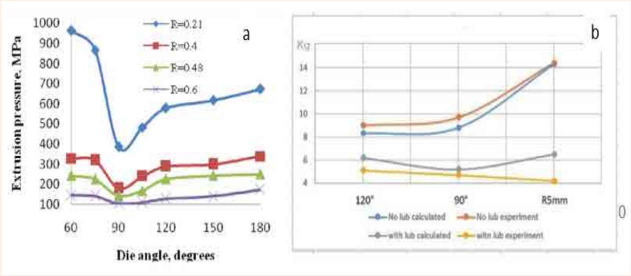

Figure 12: Die angle Vs. extrusion pressure (a) Aluminum extrusion [17] (b) Plasticine students measurements at R=10.

2.3. The influence of multiple die passes

The employment of multiple passes (holes) die is economic and it is used to increase production while reducing extrusion ratio and forces. The extrusion of Plasticine using 1, 2 and 3 openings (Figure 4) can be seen in (Figure 13). It was crucial for students to see this kind of demonstration since it is harder to convince them about the decrease of extrusion forces due to the use of multiple die passes, regarding theory only. The "metal" flow was also demonstrated using color layers (Figure 13b). All experiments were carried out using a constant extrusion ratio and die angle.

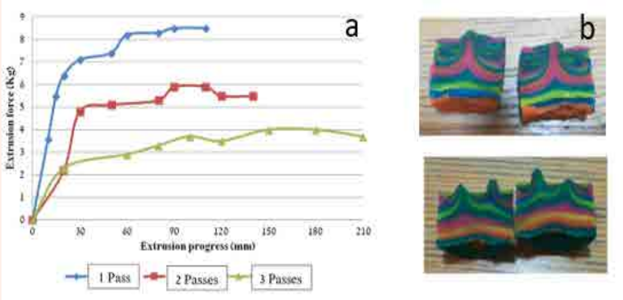

Figure 13: The influence of multiple passes die on extrusion forces.

2.4. The influence of bearing length

Die designers try to make the bearing as short as possible since the extruded profile gets its shape from the bearing and the friction between the extruded profile and bearing is extreme. A bearing that is too long will not only scratch the extruded profile, it will also increase the extrusion forces due to friction. As can be seen in (Figure 14), the influence of bearing length on extrusion forces is demonstrated compared to Aluminum extrusions [17] with the influence of lubrication.

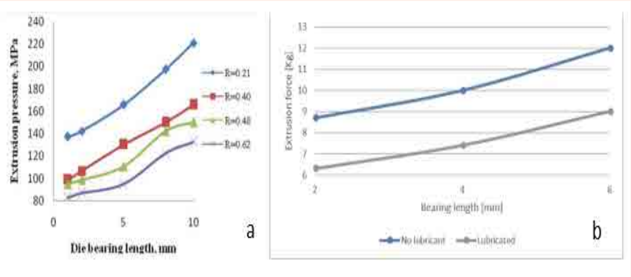

Figure 14: The influence of bearing length on extrusion pressure (a) [17] (b) students experiments.

2.5. Closed die forging with flash

A force Vs. displacement graph of the closed die forging of Plasticine can be seen in (Figure 15a). This kind of graph is typical for forging with flash, demonstrating the different stages of the process. This graph shows four different runs done by students. Data was analyzed from the videos that students took of each experiment catching force Vs. displacement on the same frame. In (Figure 15b), the influence of flash on forging forces is demonstrated when compared with the calculated values.

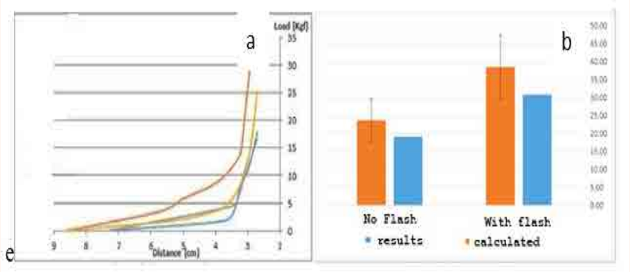

Figure 15: Impression die forging of Plasticine (a) Force Vs. Displacements (b) The influence of flash

In order to demonstrate the influence of the die profile on back-extrusion forces, four different shaped dies were 3D printed. The forces of the back-extrusion process were measured directly and compared to the calculations that were made using empirical equations. The test results that can be seen in (Figure 16) also emphasize the influence of lubrication on the back-extrusion forces. The "metal" flow was determined using color layers as can be seen in (Figure 16b).

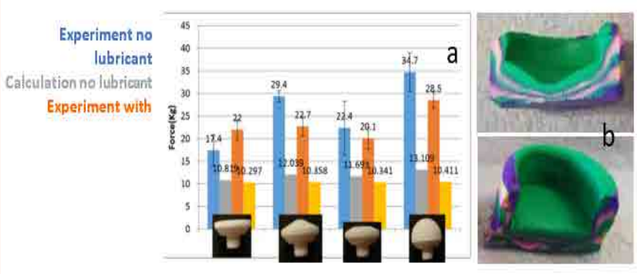

Figure 16: Back extrusion of Plasticine (a) forces using four different die shapes (b) "metal" flow.

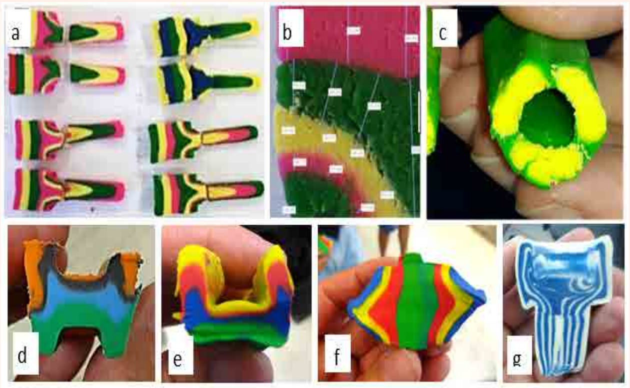

Figure 17: "Metal" flow exploring using Plasticine (a) extrusion interrupted tests (b) measuring of strain distribution in forging (c) bridge die tube extrusion flow (d, e) H and U shapes profile rolling (f) colored layers Plasticine forge with flash (g) heading.

2.6. "Metal" flow determination

The influence of tools geometry, flow stress, and friction on metal flow was demonstrated to students using colored layered Plasticine (Figure 17). Interrupted extrusion tests were performed to evaluate the influence of die profile and friction on the Plasticine flow and were compared to numerical simulations. Local strain distribution in forging was evaluated by measuring the local thickness of colored layers, then calculating the reduction of that initial thickness (Figure 17b). The "seams" of bridge die tube extrusion were also demonstrated using colored layers (Figure 17c). (Figures 17d & 17e) show the "metal" flow in the rolling of H and U shape profiles while (Figure 17f) shows the flow of metal in closed die forging and filling up the gutter. Better resolution can be achieved using thinner layers of Plasticine. The flow of metal during the heading operation can be seen in (Figure 17g). The making of the hexagonal pocket is a type of back-extrusion operation. The flow of material from the asides and the DMZ in the center are visible.

Conclusion

1. At room temperature, Plasticine can be used to predict loads, strains, strain distribution, and the influence of friction on metal forming processes.
2. Model materials such as Plasticine can be used to teach a number of metal-forming processes.
3. The flow stress and physical properties of Plasticine as a function of color, temperature and strain rates are well established, so experimental results can be compared to calculations done by students.
4. Teaching and modeling metal forming processes were found to be effective and inexpensive compared to other laboratory work.
5. Students can design and print their own dies and tools and instantly evaluate the effects of new approaches to the metal forming process.
6. It was found that students who participated in "hands on" work at the Plasticine laboratory had a better understanding of metal forming processes.

Acknowledgment

The author would like to acknowledge Prof. N. Frage for his support and encouragement during the establishment of the Plasticine laboratory class at Ben-Gurion University while he served as the head of the material science and engineering department.

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