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LUBRICATING MATERIALS AS A NOVEL APPROACH TO REDUCE DEFECTS OF MICRO-DEEP DRAWING FORMING PROCESS

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The deep drawing forming process, classified under sheet metal working, is a promising and essential metal forming process that has attracted much interest due to its wide application in micro-production. The process parameters, such as the cross-head speed of the machine, have a significant influence on the quality of the product. The impact of two essential parameters was investigated to minimize or eliminate the product's production defects, such as thinning, tearing, and scratching. The first one was the impact of using two types of lubricating oil (grease and wax), and the products were compared with the dry condition (without using a lubricating oil). The second is the impact of changing the cross-head speed of the machine from 5 to 15 mm/min. This work aims to determine the optimum operating condition that prevents any defect in the product. The results showed that using lubricating oil resulted in better product shape, and the wax is better than grease in eliminating product defects. In addition, the results showed that the lower machine speed is preferred for eliminating production defects, where the final product has no obvious thinning, tearing, or scratching. The final product shape was evaluated visually because eye observation is the only way to judge the product shape.

Keywords: sheet metal, thinning, tearing, scratching, grease, wax

1 INTRODUCTION

Metal forming, which consists of a large group of manufacturing processes, is used to change metal's shape (plastic deformation of the work-pieces). Deformation occurs when die and tool are used in metal forming [1]. According to the shape and size of the work-piece, the metal forming is classified into two main categories: sheet metal working processes and bulk deformation processes, as shown in Figure (1). Each category consists of many types of shaping operations.

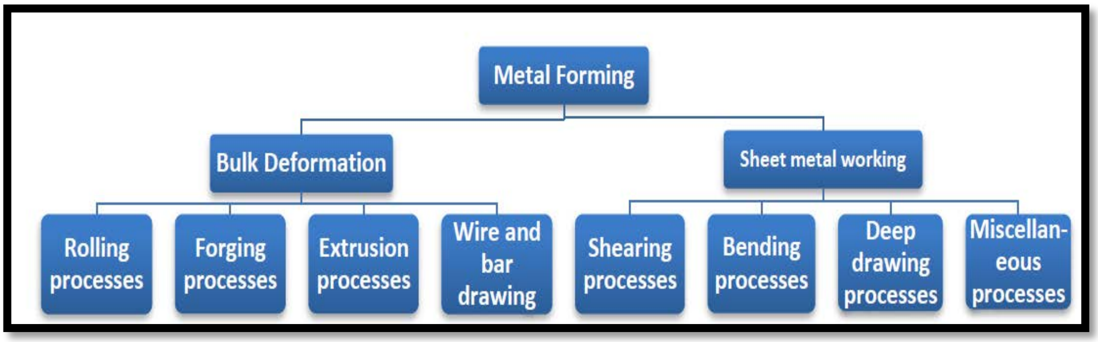

Fig. 1. Classification of metal forming processes [2]

For high-volume manufacturing, deep drawing is considered a promising and valuable process. The most important advantage of this process is its potential to manufacture components with exceptional repeatability and accuracy while reducing the manufacturing cost compared to other manufacturing methods, such as turned and machined components[3]. The process of deep drawing is a significant method in sheet metal forming. In recent years, product miniaturization has rapidly developed [4-10]. Therefore, the researchers promoted the field of micro deep drawing in advanced manufacturing applications of microproducts, focusing on decreasing their weight and volume.

Different micro-forming processes can be applied to different materials. Herein, the micro-deep drawing process on aluminum foil was chosen instead of the conventional deep drawing process because the micro-deep process forms a cup using a blank sheet of material between 0.001 to 0.300 mm thick, which is much thinner compared with that used in the conventional deep drawing (between 0.09 to 1.0 mm). In addition, the process of micro-deep drawing uses a punch between 1 and 9 mm in diameter, much smaller than that used in the conventional deep drawing (between 100 and 1000 mm) [11-14]. Several defects are often found in micro-deep drawings, such as earing on the cup edge, folding and wrinkling in the flange and cup wall, and tearing in the corner radius [15, 16].

Deep drawing, classified under sheet metal forming processes, is one of the most popular die manufacturing technologies [9]. The metal sheet, such as an aluminum sheet, is pressed through the die to form this metal with a cavity shape. The service of deep drawing and part with a cavity structure is the lowest cost and most efficient [17]. This process can be considered a deep drawing process if the depth of the drawn part exceeds its diameter. Deep drawing carried through re-drawing the part by a series of dies. The sheet metal in the die shoulder area (flange region) experiences tangential compressive stress, and radial drawing stress causes the material retention properties. These hoop stresses or compressive stresses resulted in wrinkles of the first order (flange wrinkles). Wrinkles, ears, and other defects can be decreased when using a blank holder that easily controls metal flow into the die radius. Micro-deep drawing operations, primarily in the medical industries and aerospace, require unique precision and accuracy. Sheet metal hydro-forming is pressed for complex drawing work. Stroke, bed size, speed, tonnage, and more can be tailored to any appointee draw-forming application [18].

Various process parameters were investigated in several studies aiming to optimize the deep drawing process [19]. For example, Adnan's work [20] showed that the maximum drawing force increases with the increase of the punch profile-radius, but decreases with the increase of the die profile-radius. In addition, he found that the ability of produced cups for wrinkling increases mainly with increasing punch profile-radii and secondary by die. Van et al. [21] studied the impact of friction and blank-holder pressure on earing profiles and developed a simulation model for deep drawing of stainless steel sheets. Molotnikov et al. [22] investigated the impact of blank thickness on the deep drawing process of copper (Cu) metal using mathematical modeling and experimental work. They concluded that the size effect appears if the grain size is constant while the work-piece dimensions are reduced. Vollertsen et al. [23] reviewed the micro-forming metals while performing experimental work. They stated that the friction coefficient of micro-deep drawing at the die radius and the flange is unequal and depends on the applied pressure. Brabie et al. [24] analyzed the simulation model and experimental results concerning thickness variation in the cases of micro and mil-cylindrical drawings using aluminum foil. Hadi Syamsul [11] used foil of aluminum AA1235 for micro-deep drawing and suggested refining the bulged punch lower than 130 µm to avoid the tearing in the corners and the earing at the edge of the cups, as well as reduce the wrinkling in the cup's wall. Other works also investigated the process parameters such as die radius, die clearance, punch radius, and clearance [25, 26] on failure or success of the deep drawing technique.

Unfortunately, there is still a lack of investigation on the impact of other parameters, such as the lubricating and the drawing speed. Although increasing the drawing speed is very attractive, it increases defects, which means losing resources. In addition, using dry conditions results in product defects, which also causes preliminary materials, time, and effort loss. This loss limits the application of these techniques on the industrial level. Thus, addressing the best conditions of these two parameters is essential. Therefore, this work addresses the problem of defects that occur during the drawing of thin sheets using a new additive, which is lubricant, to minimize this issue. This work aims to determine the optimum operating condition that prevents any defect in the product. Therefore, this work investigated the impact of using two lubricating types and compared the results with those without lubricating oil. In addition, this work investigated the effect of changing the drawing speed by testing three cross-head speeds of the testing machine (5,10, and 15 mm/min). These speeds and variables were adopted based on literature and what was available in the used machine. The results of this work provide more profound insights regarding the reduction of defects in the process of micro-deep drawing.

2 MICRO-DEEP DRAWING DIE DESIGN

Based on the measurements of the required final product (diameter, thickness, and height), a template is designed to draw the aluminum sheet with the required measurements through well-known design equations for the deep drawing process [27]. These equations determine the diameter of the initial work-piece, the diameter of the template, and the diameter of the piston. In addition, these equations determine the number of pulls, the required force for pulling, the shrinkage rate, and tolerances. These standards are essential for the accuracy of the dimensions of the final product, as shown in Figures (2 and 3).

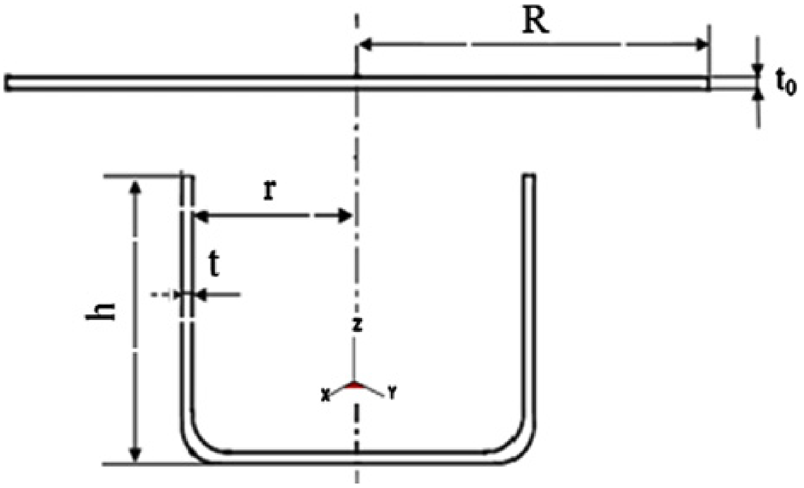

Fig. 2. Blank and drawn part dimensions

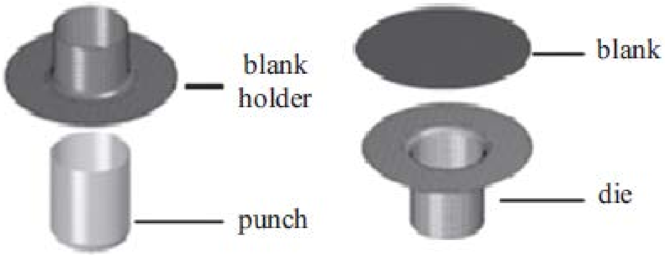

Fig. 3. Tools used in the micro-deep drawing process plotted by SOLIDWORKS-3D CAD Design Software

This work followed the general design equations suggested in the literature. To design the drawing die process, the equations from 1 to 8 should be followed [28]. The parameters resulting from these equations are highly significant because when the depth of the drawn part exceeds its diameter, the process will be considered a deep drawing process. Therefore, these equations were used to design the die. Equation 1 is used to find the initial blank diameter.

$$D=\sqrt{d^2+4dm*h} \tag{1}$$

D, d, dm, and h are the blank diameter, product diameter, product mean diameter, and product height, respectively. In this work, the values of the blank diameter (D), product diameter (dm), product length (L), and thickness (t) are 15, 5, 5, and 0.25 mm, respectively. D value was used as work-pieces to draw the final product. Equation 2 is used to find the die radius, which is 8mm, noting that the die was used as the cavity of the final product.

$$r=0.8\sqrt{(D-d)\pi} \tag{2}$$

Where r, D, and d are the die radius, the blank diameter, and the product diameter, respectively. Equation (3) is used to find the punch radius, which was found to be 32 mm. The punch is used as a press to force the blank to be drawn into the final product.

$$R = (3\text{-}5)\, r \tag{3}$$

R and r are the punch and die radius, respectively. Equation (4) is used to find clearance, which was found to be 0.26mm. The clearance means the error rate of the final product measure.

$$C = t + K\sqrt{10\,t} \tag{4}$$

C, t, and K are the clearance between punch and die, the blank thickness, and the constant factor, respectively. According to the standard tables, the K value equals 0.02 for aluminum alloy. The C value calculated from Eq. 4 is 0.266 mm. To find the drawing force, equation (5) is used [28], which is found to be 140 N/mm2. The drawing force helps to estimate how many loads need to be completed in the drawing process.

$$F= L * t * S * (D/d - C) \tag{5}$$

F, L, t, S, D, d, and C are the drawing force, the product perimeter, the blank thickness, the yield strength of metal, the blank diameter, the product diameter, and the clearance between punch and die, respectively. The strain factor is determined by using equation (6) [28],

$$E =\left(\frac{D}{d}+1\right)/2 \tag{6}$$

E, D, and d are the strain factor, the blank diameter, and the product diameter, respectively. Equation (7) is used to find the reduction ratio.

$$Rc =\frac{100(D-d)}{D}\% \tag{7}$$

Rc is the reduction ratio, D is the blank diameter, and d is the product diameter. Finally, equation (8) is used to find the strain hardening.

$$St=S \log E^n \tag{8}$$

Where St, S, E, and n are the tensile strength of metal, the yield strength of metal, the strain factor, and the strain hardening exponent, respectively. Figure (4) shows the process steps. The equations from 6 to 8 guarantee that the drawing process will occur without any trouble.

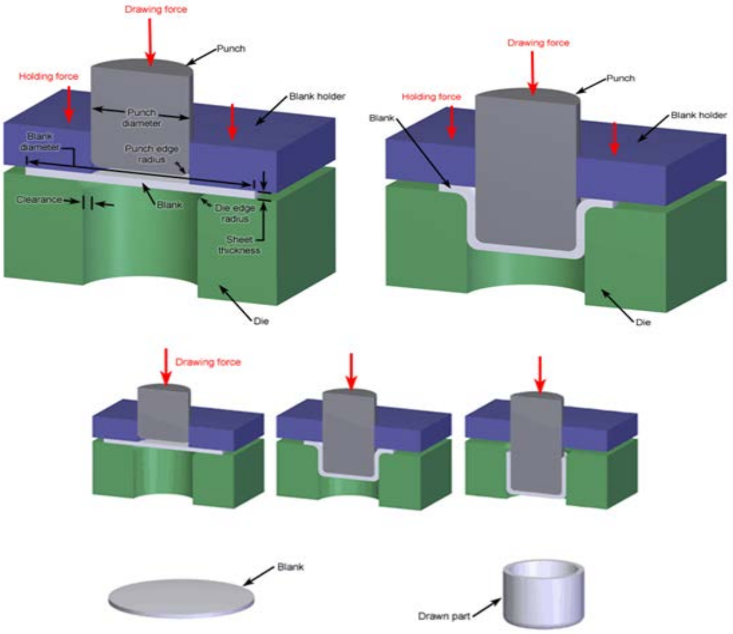

Fig. 4. Deep drawing dies step by step plotted by SOLIDWORKS-3D CAD Design Software

3 EXPERIMENTAL PROCEDURES

This work drew flat blank aluminum foil (AA1050) material in one step. The composition of aluminum foil (AA1050) is presented in Table (1). The blank's diameter, shown in Figure (5), was 15 mm, and its thickness was 0.25 mm. The die and tool of deep drawing were designed to carry out the experimental procedures required to produce a cylindrical cup with an outer diameter of five millimeters as shown in Figure (6). The micro-deep drawing process was performed using the drawing die, as shown in Figure (7). Die consists of the plates' essential parts, lower and upper. These plates were made of galvanized steel, while the die, punch, and compression springs were made of X12M die steel. The die and blank holders were galvanized carbon steel [18]. The die and punch were heat-treated according to the die's recommendation to heat-treatment to obtain the perfect hardness RC 67 after being measured by the Rockwell Hardness test [18].

The heat treatment was done in Al-Kut Technical Institute's laboratories using laboratory furnace type HERAEUS (made in England), shown in Figure (8). Steel was preheated at 850 °C after a period of heating at 1040 °C for about 40 min; then oil was as used as a quenching medium to cool these pieces to reach a temperature of 60±3 °C. After that, these pieces were cleaned to measure their hardness using Rockwell device type GNEHM (made in Russia), shown in Figure (9). Tempering was made to relieve the stress of steel at 590 °C for 30 min.

The blank holding force used was 1.202 KN. The mechanical properties of foil aluminum are shown in Table (2). In the deep drawing method, formability can be shown in terminologies limiting drawing ratio (LDR). In this work, the limiting drawing ratio used was 1.86, and the cross-head speed for the testing machine was set to 5,10, or 15 mm/min.

Two types of lubricant, grease and wax were used, and the product was compared with that resulting from the same condition but without lubricating. The lubrication technique used is the Internal Force Feed and Splash System. In this method, the pump pushes the oil directly into the engine body instead of the spray container, and from there, the oil rushes through the passages to the main axes, the camshaft axes, the crankshaft, the rocker arm shaft, and finally to the oil pressure measurement unit. The type of lubricating wax is Mobil DTE 24 Ultra.

The comparison aims to show the ability of lubricating to reduce defects such as earing, folding, tearing, and wrinkles that can occur in products of micro deep drawing processes. All experiments were triplicated, and good repentances were observed in the shape of the final products under each condition.

Table 1. Actual versus standard compositions of AA1050 Aluminum alloy (wt.%)

Elements	Si	Fe	Cu	Mn	Mg	Zn	Ti	Al
Standard Value	0-0.25	0-0.4	0-0.05	0-0.05	0-0.05	0-0.07	0-0.05	Balance
Actual Value	0.078	0.234	<0.0005	0.006	0.0004	0.014	0.004	Balance

Fig. 5. Dimension of blank (work-piece)

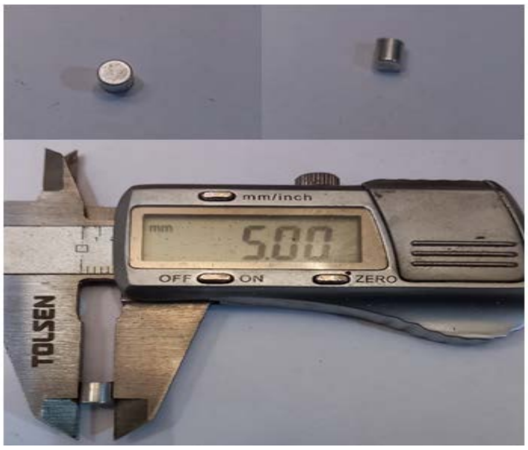

Fig. 6. Dimension of the cylindrical product (drawn part)

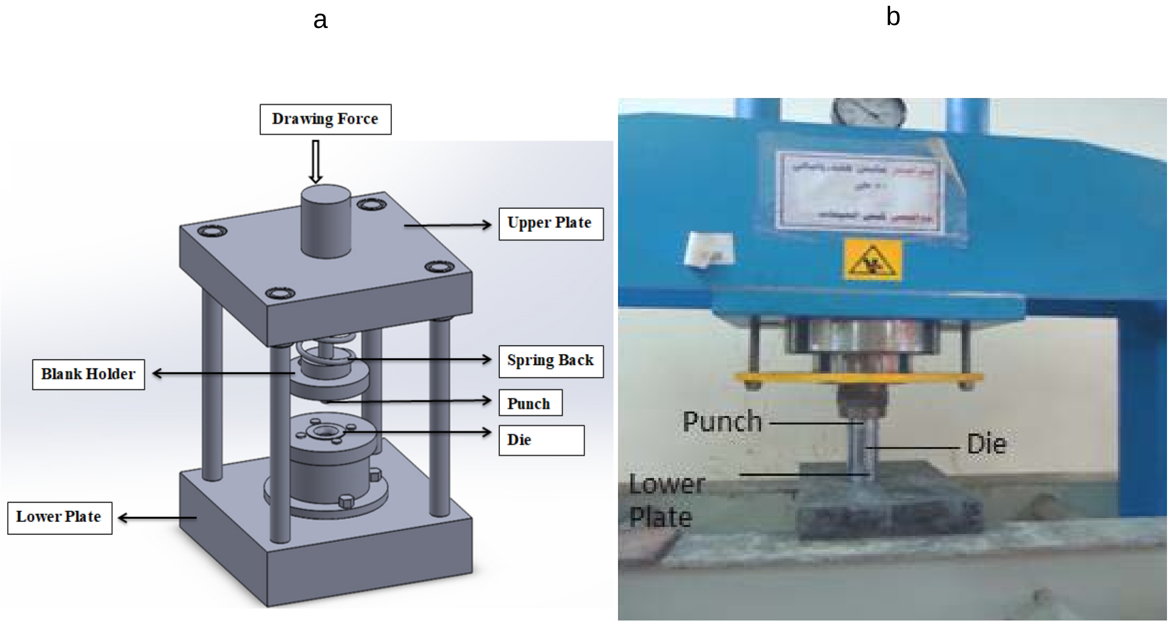

Fig. 7. (a) Design of micro-deep drawing die plotted by SOLIDWORKS-3D CAD Design Software and (b) the real Hydraulic Press used during the deep drawing Process

Fig. 8. Laboratory furnace used for heat treatment

Fig. 9. Device of Rockwell Hardness test

Table 2. Actual versus standard mechanical properties of AA1050 Aluminum alloy

Property	Proof stress MPa	Ultimate stress Mpa
Standard Value	95	105
Actual Value	112	119

4 RESULTS AND DISCUSSION

4.1 Effect of Lubrication

The lubricant's viscosity is one of the essential parameters for optimizing micro-drawing processes due to the high-velocity dependency on the friction between the blank and punch [17]. This work tested three statuses of lubricating, which are dry (without lubricating), with grease, or with wax, during the drawing process. The products of the three cases and the different speeds of the machine are presented in Figure (10 a-b-c). At the lowest speed (5 mm/min), the best product in terms of shape clearness results from using wax. Wax lubricating resulted in fewer defects than the other two products while using grease lubricating did not prevent the appearance of some defects as detected visually. This indicates that not all types of lubricating are appropriate to eliminate the defects or improve the product ideally. The type of lubricating oil is crucial to this aim in this process. Significantly, lubricant reduces the cracks and growths that usually appear on samples drawn without oil or with grease oil. This new technique has yet to be used previously. It dramatically benefits manufacturing operations, especially precision ones that require dimensional accuracy, as this process reduces damaged metal, saves time and effort, and prolongs. It extends the life of the drawing die, facilitates product extraction, and reduces defects such as wrinkling, rims, nicks, and cracking of the rims, which are a weak spot and the starting point for metal failure. The dry process showed a worse shape due to the highest defects, such as thinning, tearing, and scratching, that appeared in the product (cup). Increasing the speed to 10 and 15 mm/min increased the defects mainly in the dry process, while the less product impacted by increasing the speed was that produced with wax lubricating.

Wax is a material with a high viscosity, even higher than grease. Therefore, it has been found that it facilitates the drawing process, preserves the drawing mold or template from corrosion, reduces friction between the product and the mold, prolongs the life of the mold, and reduces losses in the drawn metal. Thus, the product's defects were reduced, and its measurements were more accurate. The visual inspection of the drawn samples manufactured using wax shows that the products are free of rips and tears, as seen in Figure 10.

4.2 Effect of Drawing Speed

Figure 10 (b and c) shows that the earring phenomenon and torn were observed during experiments by visual test when using a high-speed testing machine because the sheet metal for work-pieces is skinny. The hydraulic press (KNUTH, made in Germany, shown in Figure 7-b) was linked to the micro-deep drawing die to supply enough force at different speeds [1]. In this work, three cross-head speeds (5-10-15) mm/min were used, and the effect of increasing the speed machine on maximum load was studied. When the speed of the testing machine was 5 millimeters per minute, the maximum recorded value of punch load was 3 KN for wax and 2.5 KN for grease as shown in Figure (11). Increasing the speed of the testing machine to 10 mm/min led to an increase in the maximum value of punch load to 3.75 KN for wax and 3.0 KN for grease, as presented in Figure (12). A comparable trend was observed when the speed increased to 15mm/min, which led to a rise in the maximum punch load to 4.0 KN for wax and 3.5 KN for grease, as shown in Figure (13). The higher punch load values recorded compared with grease indicate that lubricating with wax facilitates the pulling process and reduces the required force or the load applied for the pulling process. This is one of the benefits of pulling with wax lubricating while pulling without oiling or oiling with grease requires higher force.

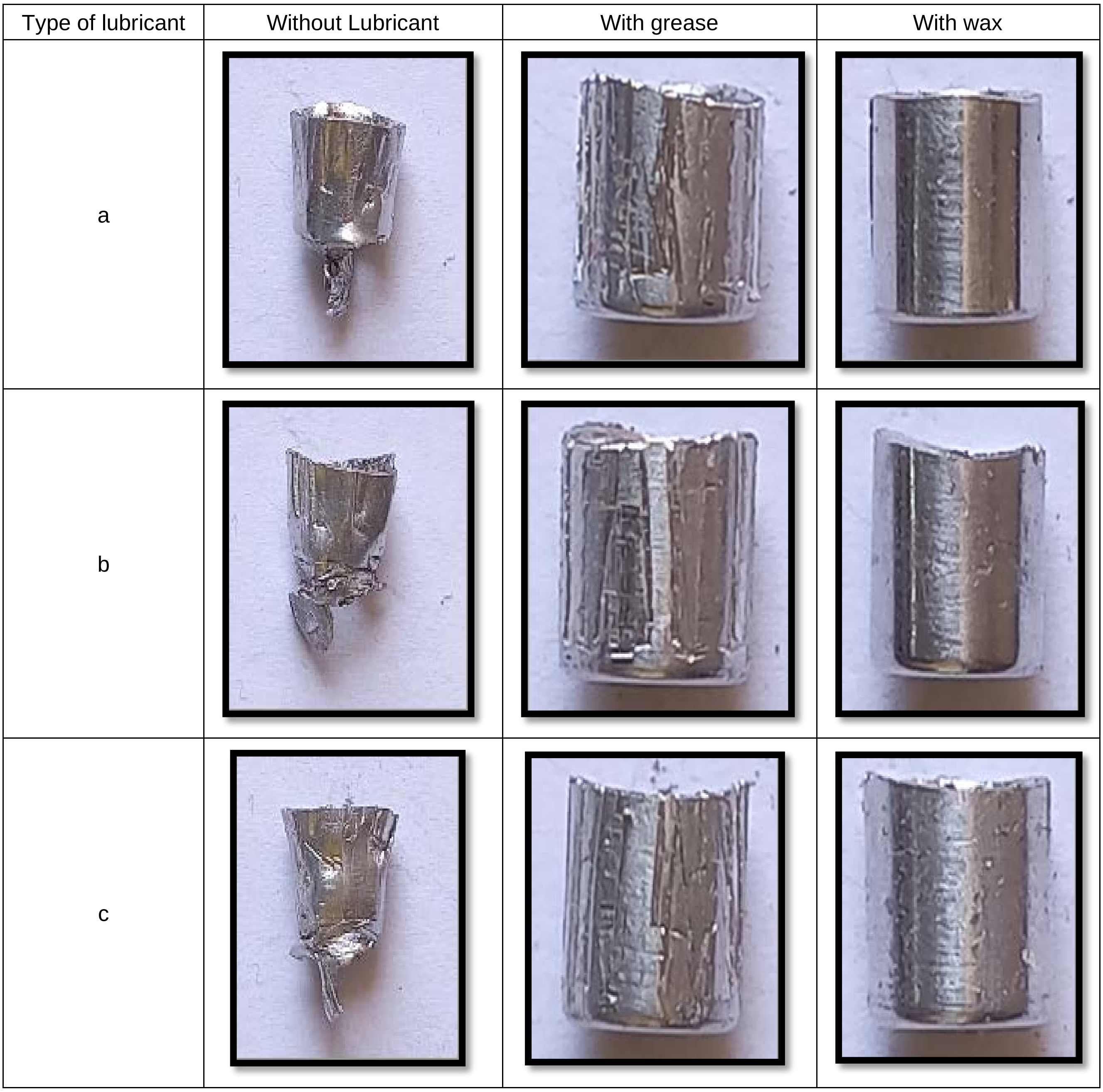

Fig. 10. The influence of type for lubricant on product's shape at a speed of (a) 5 mm/min, (b) 10 mm/min, and (c) 15 mm/min

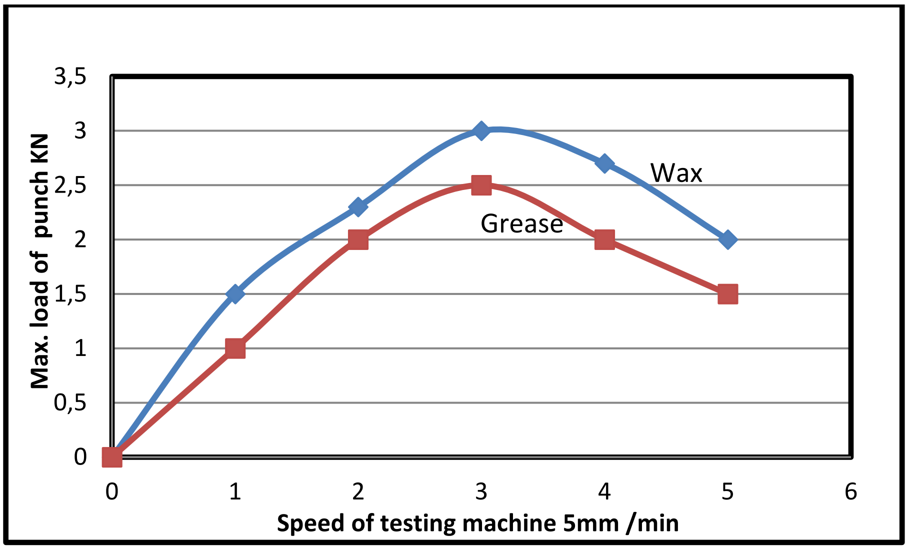

Fig.11. Effect speed of the testing machine on the maximum punch load when drawing with wax against grease oil

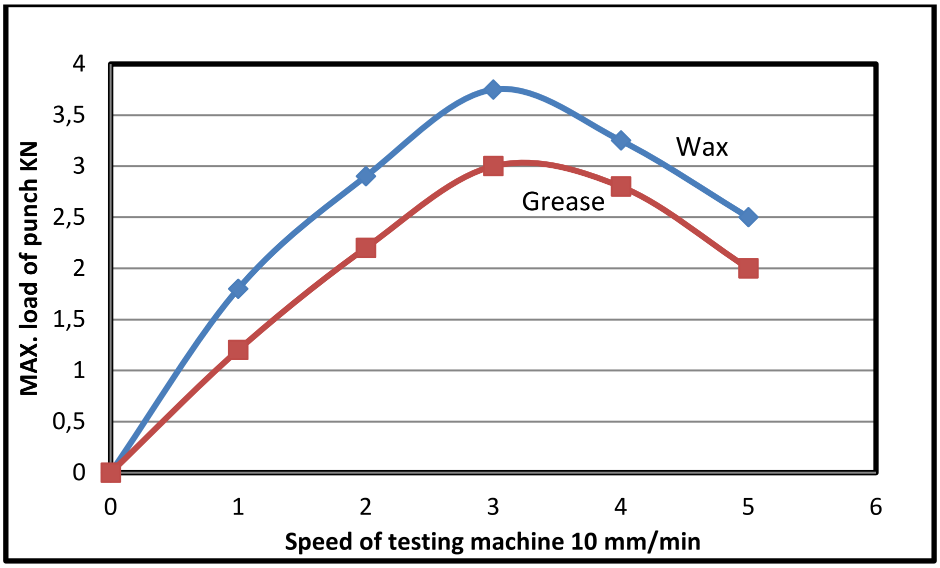

Fig. 12. Effect speed of the testing machine on the maximum punch load when drawing with wax against grease oil

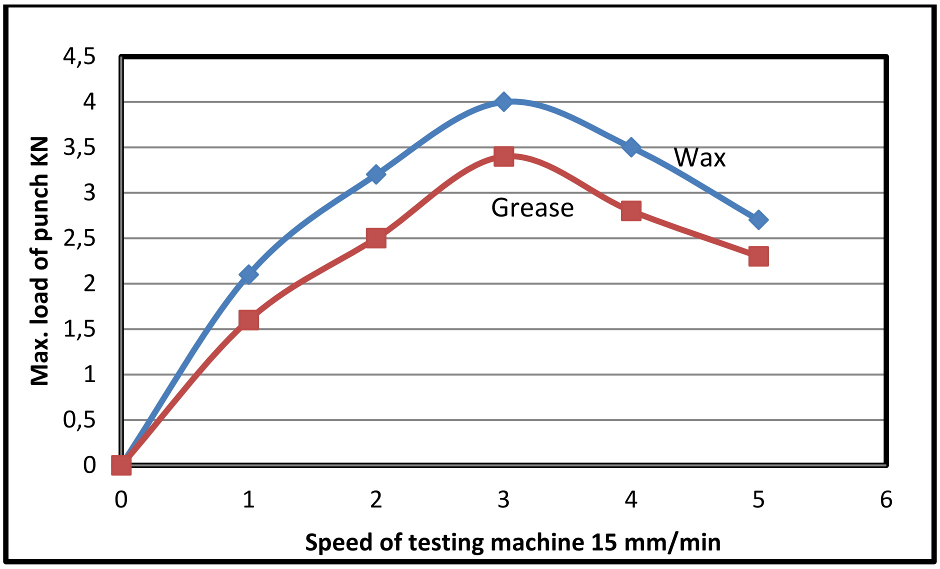

Fig. 13. Effect speed of the testing machine on the maximum punch load when drawing with wax against grease oil

From the above figures, the increase in the speed testing machine led to an increase in the max load punch, and the best case for the micro-deep drawing process takes place when using wax for lubricant. That clearly shows the improvement of products and the easy process of micro-deep drawing using a lubricant (wax), as presented in Figure (14). The lowest speed (5 mm/min) resulted in the best shape. Higher speed is preferred for increasing productivity. Thus, lowering the speed below 5 mm/min is not preferred, even if it results in a product without defects. From the visual observation of the products (Figure 10), it can be concluded that the lubrication factor is more potent in preventing shape defects than the speed factor.

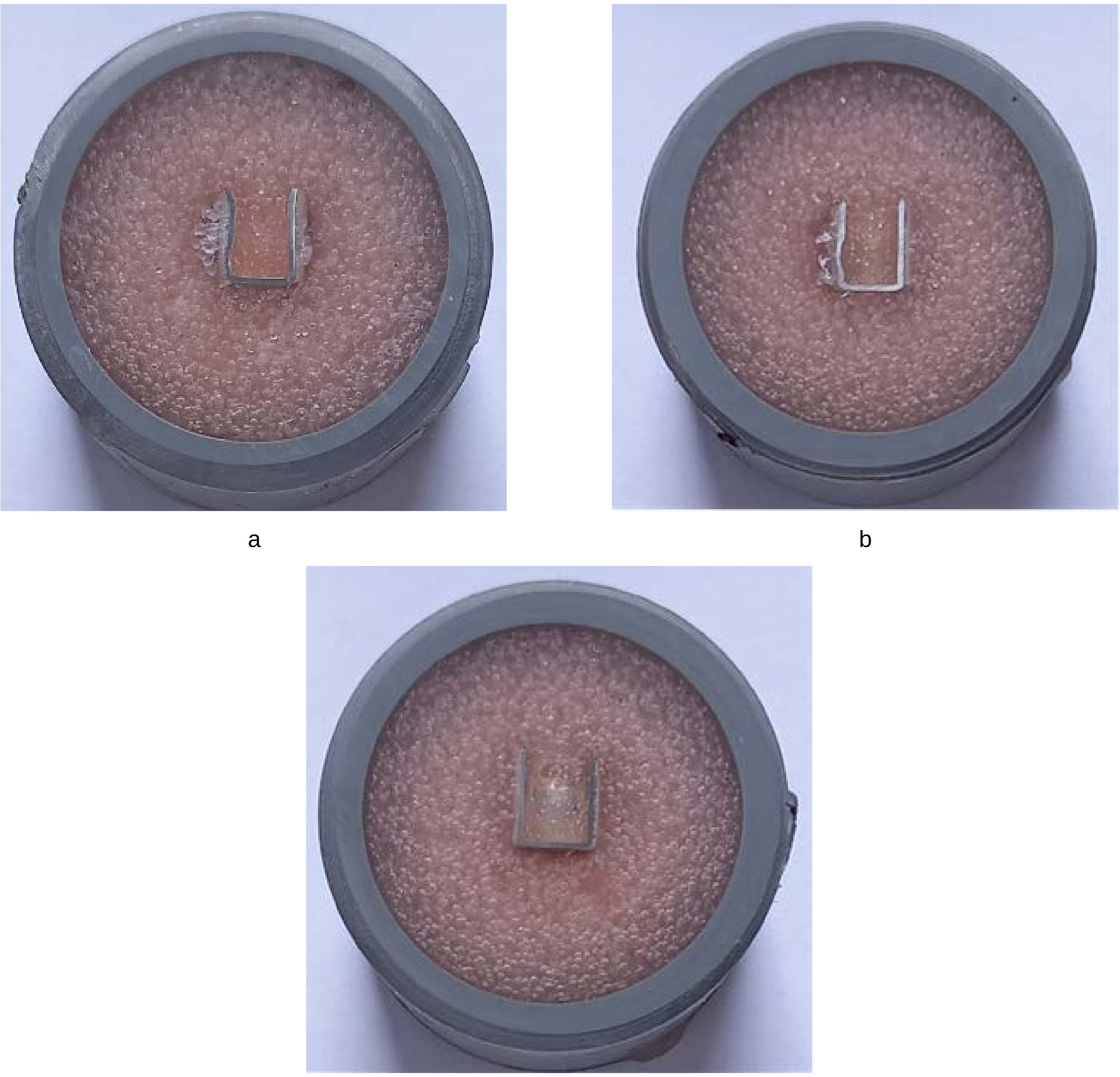
a
b
c

Fig. 14. Micro drawing process with wax lubricant at different punch speeds. (a) 5 mm/min, (b) 10 mm/min, and (c) 15 mm/min

5 CONCLUSION AND FUTURE PERSPECTIVES

From the experiments, lubricating improves the product and decreases the defects. It was found that lubrication has a significant impact on the quality of the product. Visual inspection of the product proved that the best lubricant is wax, which showed better production quality than that produced with the use of grease in terms of reducing defects. Although using grease resulted in better product quality than that produced under dry conditions, it only minimizes the defects but does not prevent them. This new technique has yet to be used previously. It dramatically benefits manufacturing operations, especially precision ones that require dimensional accuracy, as this process reduces damaged metal, saves time and effort, and prolongs. The increase in the speed of the machine resulted in an increase in the maximum load for all cases of lubricants, and that increased defects. The best speed was 5 mm/min, and the best lubricating oil medium was wax. This study focused on these two parameters due to the lack of sufficient information in the literature and their independence, which helps to exclude other operational parameters and keep them constant during this investigation. The use of new lubricants for forming processes is recommended for future work due to the promising ability to minimize metal losses, defects, and the required force. These new materials, such as wax, with granules of nanomaterial, such as graphene, can significantly improve the drawing process.

6 ACKNOWLEDGMENT

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