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THE EFFECTS OF THE DIE HALF ANGLE OF TAPER DIE ON PLANE STRAIN EXTRUSION

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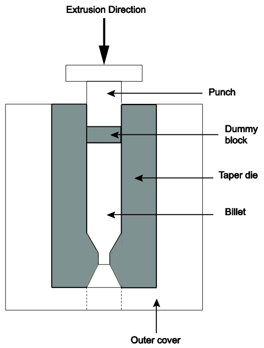
Graphical abstract



Abstract

In this research, a study of the effect of a die half angle on the extrusion process has been performed. The experiments were conducted at room temperature around 27 °C. Two types of taper die with different die half angles (45° and 60°) were prepared. The test lubricants used were paraffinic mineral oil VG460 and Refined, Bleached and Deodorized (RBD) Palm stearin. The material of the workpiece (billet) was annealed with A1100 aluminium. The experimental results were focused on the extrusion load, tool and workpiece surface roughness and plastic deformation of the workpiece. The resultant relative velocity was calculated using a visioplasticity method. The results shows that a taper angle of 60° recorded higher resultant relative velocity with a lower extrusion load and surface roughness compare to the taper angle of 45°. The comparison study between Paraffinic Mineral Oil and RBD Palm Stearin shows no significant effect in both taper angles tested.

Keywords: Die half angle, extrusion, paraffinic mineral oil, RBD palm stearin, visioplasticity, extrusion load, surface roughness

1.0 INTRODUCTION

By definition, an extrusion is a compression-forming process in which the specimen is forced to flow through a die opening to produce a desired shape. Extrusion has become one of the most popular metal-forming techniques in industries. This is because of its advantages, such as no full utilisation of the material, a higher dimensional accuracy, good surface quality and the elimination of subsequent operations. There are two types of extrusion: hot extrusion and cold extrusion. In hot extrusion, the process is performed at an elevated temperature, whereas the cold extrusion process is performed at room temperature. Moreover, both methods can be achieved using forward extrusion or backward extrusion [1].

The extrusion process is a technique that involves high pressure and requires a high load to overcome friction. Thus, the dies and workpieces (billet) used in extrusion are the main parts subjected to severe working conditions. Manufacturers are trying to avoid a high working load as much as possible, because the high value of the frictional coefficient could produce many errors in the extruded component . This will lead to a low quality product, as well as will shorten the die life [2]. Over the years, researchers have continued seeking solutions to improve the quality of the extrusion process. Some factors affect the extrusion process: die shape, billet properties, the frictional constraint condition and the lubrication condition. Various types of lubricants have been proposed as alternative metal-forming lubricants other than conventional mineral or synthetic oil [3-5].

The geometric characteristics of die tools are crucial, as they influence the extrusion process and mechanical properties of a product. Some examples of geometrical characteristics include die reduction ratio, loading rate and die angle. A proper selection of die angle could help reduce the extrusion load and create a better flow deformation. Chaudhari *et al*. [6] stated that with an increasing die land length, the extrusion required to extrude the workpiece also increases. This is because the increase in die land length creates a larger contact area between the die tools and the workpiece. However, in the research conducted by Syahrullail *et al*. [7], the die land length was not the function affecting forming load. This is likely because the lubricating condition cancelled out the die land length factor.

In this research, the effects of the die half angle of a taper die on a billet extruded with two different taper die angles are analysed and compared. The billet material used is pure aluminium A1100. The test lubricants are paraffinic mineral oil VG460, RBD palm stearin. The selection of palm oil as lubricant was due to the ability to create a thin film and reducing metal to metal contact [8-9]. This research follows the efforts done in the research to study the suitability of vegetables oil as lubricant using Jatropha Oil, Castor Oil, Double Fractionated Palm Olein and Palm Fatty Acid Distillate with different speed, load and temperature both compared with commercial engine oil [10-13]. The experiment is conducted at room temperature. The extrusion load from the experimental work is recorded. The surface roughness of the billets is measured. The metal flow of the billet in the deformation area was analysed using the visioplasticity method.

2.0 METHODOLOGY

2.1 Experimental Apparatus

Figure 1 shows a schematic sketch of the plane strain extrusion apparatus used in the experiments. The main components are container wall, taper die and workpiece (billet). Figure 2 shows the schematic sketch of the billets used in the experiments. The billet material is pure aluminium A1100. The billets' shape was made using an NC wire cut electric discharge machining device. Two similar billets were stacked and used as one billet unit. One side of the contact surface of the combined billets was the observation plane of the plastic flow in the plane strain extrusion. The observation plane is not affected with the frictional constraint by the parallel sidewalls. On the observation plane, a square grid pattern measuring the material flow in the extrusion process was scribed using the NC milling machine. The lines were V-shaped grooves 0.5 mm deep, 0.2 mm wide and at a 1.0-mm interval length. The billets were annealed before the experiments.

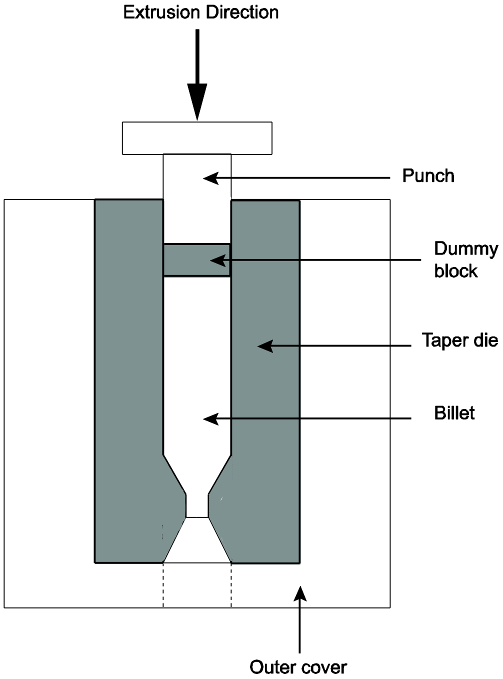


Figure 1 Schematic sketch of plane strain extrusion apparatus

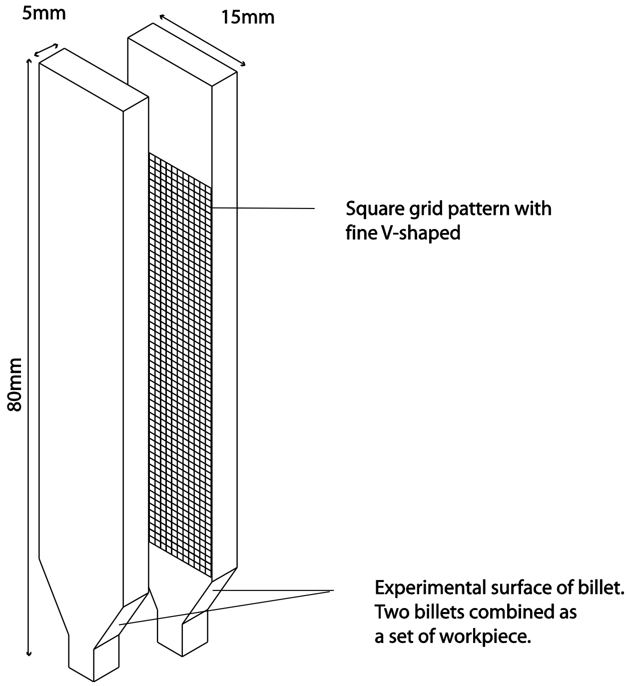


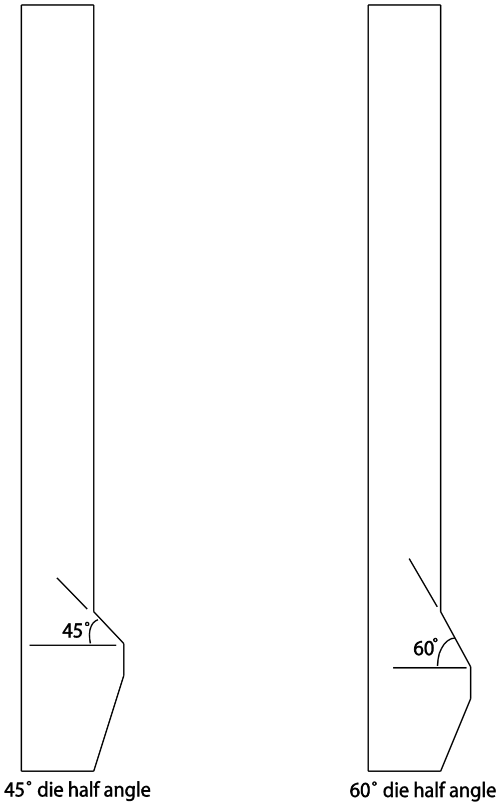
Figure 2 Schematic sketch of billet

2.2 Taper Die

There were two taper die angles used in this experiment: 45° and 60°. Figure 3 shows the schematic sketch of the respective taper dies. The taper die is made of tooled steel SKD11, and necessary heat treatments were performed before the experiments. The experimental surfaces of the taper dies (surface in contact with the billet) were polished with abrasive paper and had a surface roughness Ra of approximately 0.15 µm. A total of 15 mg of a test lubricant was applied to this surface before the experiments. The other surfaces of the experimental apparatus had the same type of test lubricant applied.

2.3 Lubricants

The testing lubricants used are RBD palm stearin and additive-free paraffinic oil VG460. Palm stearin is the solid fraction obtained by the fractionation of palm oil after crystallisation at a controlled temperature, whereas additive-free paraffinic oil VG460 is a mineral oil widely used in industries. The properties of RBD palm stearin and additive-free paraffinic mineral oil VG460 are shown in Table 1. The testing lubricant was applied to the experimental surface of the taper die before the experiment. The amount of test lubricant applied was 15 mg.



45˚ die half angle

60˚ die half angle

Figure 3 Types of taper die

2.4 Experimental Procedure

Figure 4 shows the hydraulic pressing machine. The plane strain extrusion apparatus was assembled into the confinement fixture and placed on the pressing machine. The forming load and displacement data were recorded by a computer. The experiments were carried out at room temperature with a constant extrusion load and extrusion speed. The extrusion process was stopped at a piston stroke of 40 mm.

After the experiment, the partially extruded billets were taken out of the plane strain extrusion apparatus, and the combined billets were separated for the surface roughness measurement and metal flow analysis.

2.5 Visioplasticity

Partially extruded billets were taken out of the extrusion apparatus and the combined billets were separated. The lines parallel to the extrusion direction in the grid lines on the observation plane of the plastic flow of a billet become curved lines and represent the plastic flow lines in the steady state extrusion condition. Figure 5 shows the schematic diagram of the x-y orthogonal coordinates system and the equations used in the analyses of the deformation condition. Since the analytical calculation procedure was explained in earlier publications, it is omitted here [14].

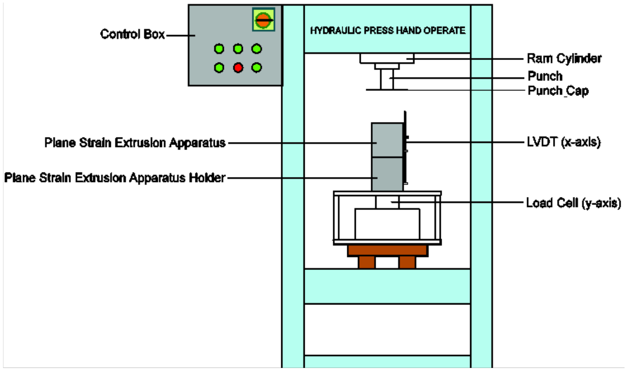


Figure 4 Schematic sketch of hydraulic pressing machine

Flow function:

$$\varphi_i = X_i|V_o|$$

Velocity component (velocity in the x-direction: u, velocity in the y-direction: v):

$$u = \frac{\partial \varphi}{\partial Y}, v = -\frac{\partial \varphi}{\partial X}$$

Strain rate component (s^{-1}):

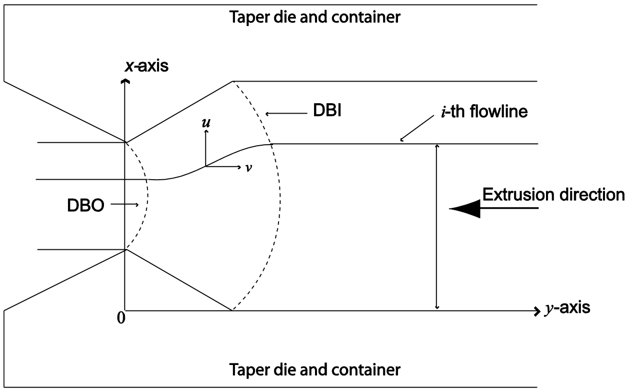
$$\dot{\varepsilon}_X = \frac{\partial u}{\partial X}, \dot{\varepsilon}_Y = \frac{\partial v}{\partial Y}, \dot{\gamma}_{XY} = \frac{\partial u}{\partial Y} + \frac{\partial v}{\partial X}$$

The effective strain rate (s^{-1}):

$$\dot{\epsilon} = \frac{2}{3}\sqrt{3\dot{\varepsilon}_X^2 + \frac{3}{4}\gamma_{XY}^2}$$

The effective strain (time integration value of the effective strain rate along the flow line):

$$\varepsilon = \int \dot{\varepsilon} dt$$



DBO: Deformation boundary at outlet
DBI: Deformation boundary at inlet

Figure 5 Coordinate system used in analysis

3.0 RESULTS AND DISCUSSION

3.1 Result and Discussion

Figure 6 shows the extrusion load-piston stroke curve. The experiment temperature was around 27 °C. The ram speed for all of the processes was constant, averaging 8.4 mm/s. As shown in the figure, the extrusion load in the process reached its steady state around a piston stroke of 35 mm. The steady state extrusion loads for paraffinic mineral oil VG460 and RBD palm stearin of a 45° die half angle are 54.42 kN and 72.59 kN, respectively. As for the 60° die half angle, the steady state extrusion loads for the billet extruded with paraffinic mineral oil VG460 and RBD palm stearin are 41.75 kN and 51.79 kN, respectively.
Both specimens extruded using a taper die at a 60° die half angle have lower extrusion load than the billets extruded with a 45° die half angle. This is because at 45°, the high turning angle has restrained the flow of metal inside the billet. As a result, a greater extrusion load is required to change the direction of the metal flow [15]. The effect of die land length was not obvious here, as the lubricant reduced the metal-to-metal contact between the contact surfaces of the taper die and the billet. When comparing mineral oil VG460 and RBD palm stearin, the billet extruded with mineral oil VG460 showed a lower extrusion load than the billet extruded with RBD palm stearin in each taper die. This is because mineral oil VG460 is able to form a thick lubricating film along the contact surfaces, lowering the chance of metal-to-metal contact between the die workpiece and the then-decreasing extrusion load.

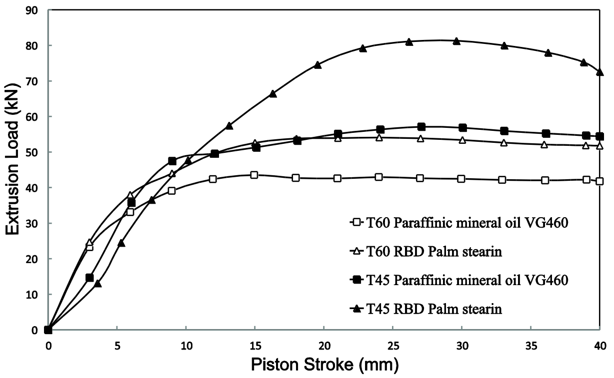


Figure 6 Extrusion load against piston stroke curves

3.2 Surface Roughness

Billets were scaled and categorised into three regions: product region, deformed region and un-deformed region, as illustrated in Figure 7. The average value of the arithmetical mean deviation of the experimental surface of the billet is shown in Figure 8. These values were measured in the direction perpendicular to the extrusion direction. Generally, the trend of the surface roughness of a billet was the highest at the un-deformed region, which then gradually decreased at the deformed region, reaching a minimum at the product region. The surface roughness at the product region is analysed and compared, as the product region reflects the roughness of the product in real life. As referred to in Figure 8, both billets extruded with paraffinic mineral oil VG460 have lower surface roughness values than the billets extruded with RBD palm stearin. On the other hand, the billet extruded using a 45° taper die has a lower surface roughness than the same type of lubricant using a 60° taper die. This shows that the die angle does not play much of a role in affecting the surface roughness of the billet as compared to the lubrication condition. Paraffinic mineral oil VG460 is a lubricant with a high viscosity. As a billet undergoes deformation, VG460 is able to form a thick lubricating film that separates contact surfaces, reducing metal-to-metal contact [16].

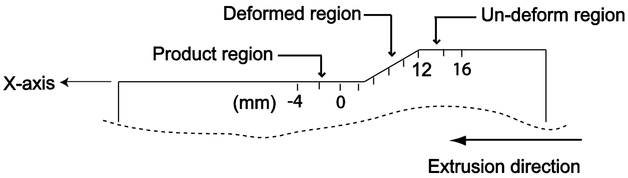


Figure 7 Product, deform and un-deform region

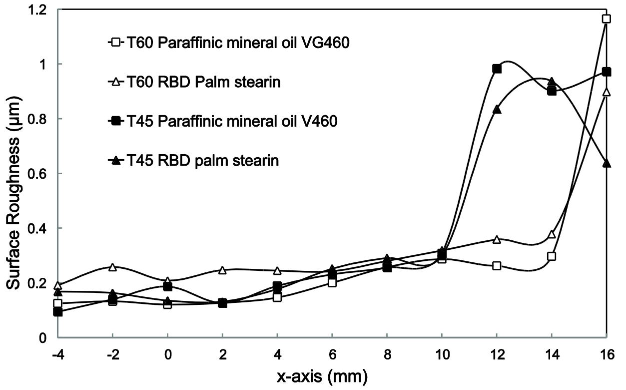


Figure 8 Surface roughness, Ra, of the experimental surface of billet

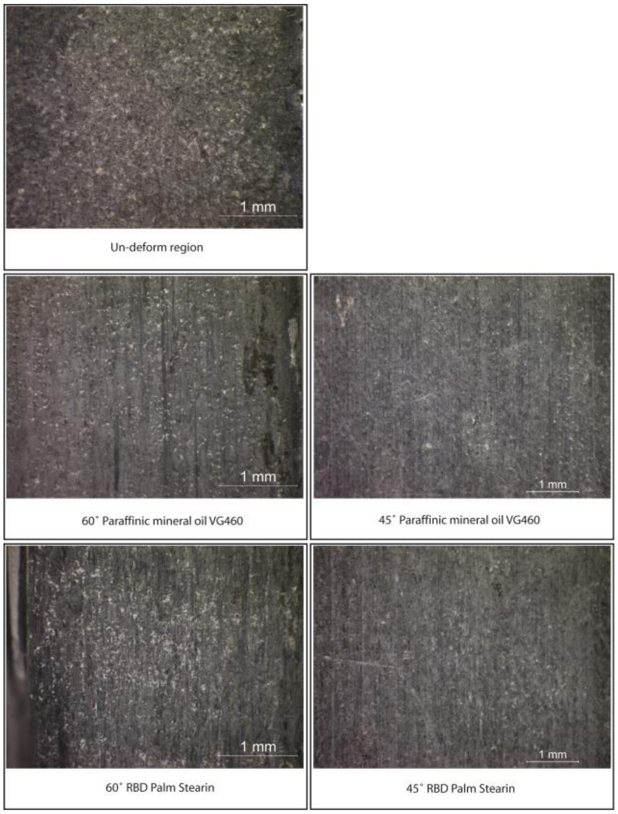
3.3 Surface Texture

The surface texture was observed using a Charge Couple Device (CCD) camera to capture the images. Observations have been made on the product region, at a location of -4 mm. Figure 9 shows the image captured from the CCD camera. It can be seen that the surface at the product region is smoother than at the undeform region. Overall, no wear damage was found on the surface of the billet.

In addition, Figure 10 presents the CCD image of a taper die surface before and after extrusion. The CCD image taken before extrusion has a similar surface texture as after extrusion, suggesting that the deformation of the billet has no effect on the die surface.

3.4 Flow Angle

Figure 11 shows the billet after extrusion, where Point A is a grid line of the undeformed region. It was found that the angle of the vertical grid line is perpendicular to the edge of the billet. As the billet was deformed, the vertical grid line must follow the extrusion flow, causing it to deviate from the right angle, as shown in Point B. By comparing the flow angle around 2 mm to 6 mm in Figure 12, the billet extruded with a 45° taper die has a lower flow angle than the billet extruded with a 60° taper die. As explained by Wang *et al.* [17], metal-to-metal contact between the die surface and the billet creates a friction force. This force prevents the edge of the billet from flowing towards the extrusion direction. The relative flow speed on the edge became slower than the flow on the inside. As a result, the vertical grid line started to deviate from the right angle to a certain angle. The result is related to the extrusion load of the billet: the higher the extrusion load, the higher the friction on the billet.



Un-deform region

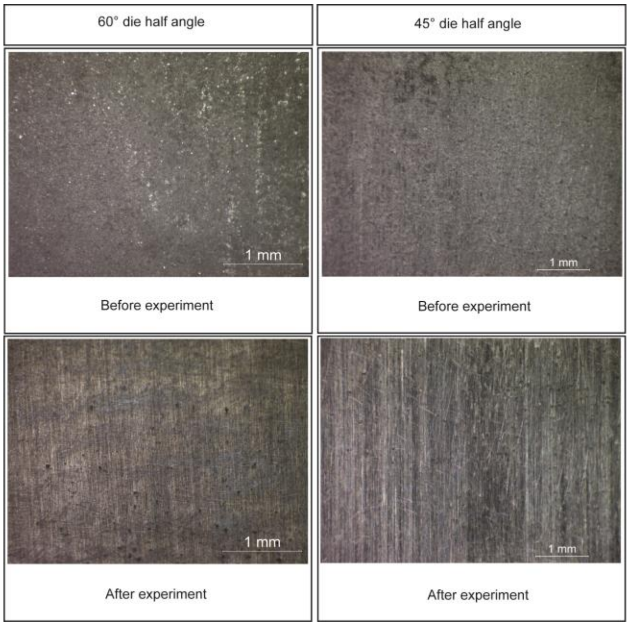
60° Paraffinic mineral oil VG460

45° Paraffinic mineral oil VG460

60° RBD Palm Stearin

45° RBD Palm Stearin

Figure 9 CCD images of extruded billet



60° die half angle

45° die half angle

Before experiment

Before experiment

After experiment

After experiment

Figure 10 CCD images of taper die

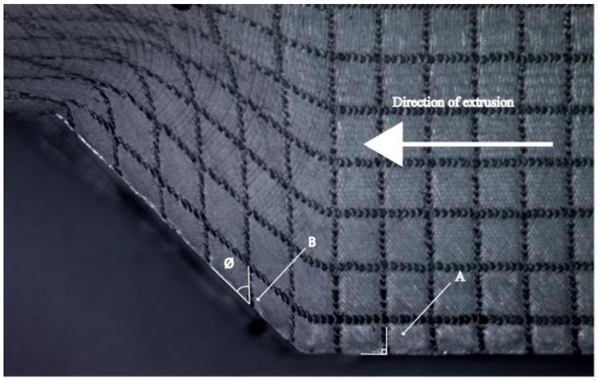


Figure 11 Condition of grid line of billet before and after extrusion

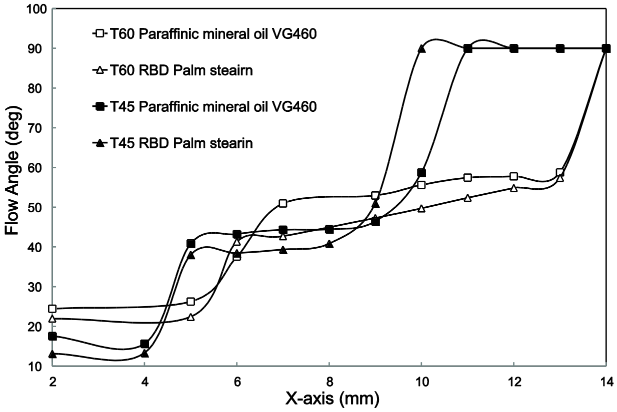


Figure 12 Flow angle of the experimental surface of billet

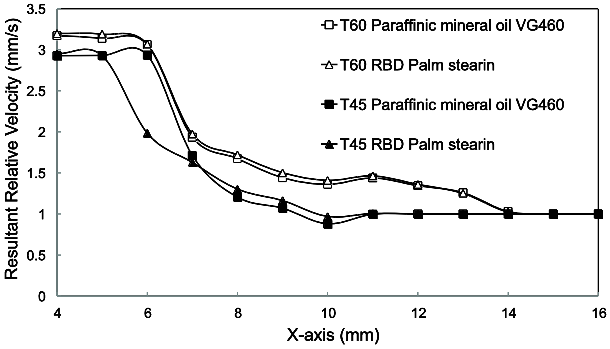


Figure 13 Resultant relative velocity along the experimental surface of billet

3.5 Relative Velocity

The distribution of the resultant relative velocity along the experimental surface of the billet is shown in Figure 13. The trends of the resultant relative velocity decrease as it moves to the product region and achieves its steady state in its value. In the deformed region, from 0–6 mm, the billet extruded with 60° and 45° taper die angles has a higher resultant relative velocity than in the un-deformed region. The taper die with a 60° angle recorded a slightly higher value of relative velocity than the taper die with a 45° angle before becoming stable at the end of the extrusion process.

4.0 CONCLUSION

Palm oil has been chosen for this comparative study with paraffinic mineral oil in order to find substitute renewable resources. Comparative studies have been conducted on both oils to determine the effects of different taper die angles and to observe the significant effects of extrusion load, plastic deformation, workpiece and tool surface. The results show that a taper angle of 60° has a higher resultant relative velocity but a lower extrusion load and surface roughness than a taper angle of 45°. It can be concluded that a taper die angle of 60° performed better than a taper die angle of 45°, and there is no significant difference between paraffinic mineral oil and RBD palm stearin in this research study.

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