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Investigation of Chip Formation Characteristics during Surface Finishing of HDPE Samples

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Abstract**—**Chip formation characteristics are investigated during surface finishing of high density polyethylene (HDPE) samples using a shaper machine. Both the cutting speed and depth of cut are varied continually to enable observations under various machining conditions. The generated chips are analyzed in terms of their shape, size, and deformation. Their physical appearances are also observed using digital camera and optical microscope. The investigation shows that continuous chips are obtained for all the cutting conditions. It is observed that cutting speed is more influential than depth of cut to cause dimensional changes of chips. Chips curl radius is also found to increase gradually with the increase of cutting speed. The length of continuous chips remains always smaller than the job length, and the corresponding discrepancies are found to be more prominent at lower cutting speed. Microstructures of the chips reveal that cracks are formed at higher cutting speeds and depth of cuts, which is not that significant at low depth of cut.

Keywords**—**HDPE, surface-finishing, chip formation, deformation, roughness.

I. Introduction

MATERIALS with good machinability usually require little power to cut, obtain a good surface finish, and maintain the tool wear within an acceptable limit. It is important to note that the conditions that usually improve a material's performance often degrade its machinability. Therefore, in order to ensure economic manufacturing of components, it is of almost importance for the engineers to find suitable ways to improve machinability without causing harm to the performance. It is quite difficult to predict machinability since a large number of variables are involved in the process of machining. These variables may be broadly classified into two categories. One of them is the physical and mechanical properties of the work material, such as microstructure, hardness, strength, etc. The other one describes the process which are to obtain the material, for example, heat treatments, work hardening, etc. In addition to the above variables, factors related to operating condition such as operating environment, cutting tool material and its geometry, machining process parameters etc. also play important role in defining the machinability of the material [1], [2]. Nowadays, plastic materials are being used extensively for manufacturing various products, because of their high specific properties of strength and stiffness compared to metals. In addition to that when compared to metal, they offer interesting opportunities for new product design because of a number of practical issues like nonhomogenity, anisotropy, etc. Although these very special characteristics make the plastic materials very attractive for specific applications, these materials sometimes become very difficult to machine because of their nonhomoginity, anisotropy as well as reinforcement by very abrasive components. As a result, significant damage to the work piece may be introduced and the cutting tools may experience high level of wear rates. In fact, the work place will experience plastic deformation when it is subjected to some machining operation and the associated degree of plastic flow directly affects the type of chips to be formed [3], [4]. Chips in practice are found to assume one of the three basic forms, namely discontinuous chip, continuous chip and continuous chip for built-up-edge. For evaluating the machining performance of a material, chip morphology is commonly considered to be an important factor. It has been reported that chip characteristics depends on work material properties, tool geometry, cutting parameters and cutting conditions [5], [6]. A comprehensive understanding of the mechanism of chip formation is of fundamental importance, as it explains how the material properties are related to surface integrity, machinability and other machining characteristics [7].

It would be worth mentioning that the chip formation characteristics, especially the comparative analysis of chip morphology in different direction during the machining of polymer materials have not yet been well explored. The present research is thus an attempt to investigate the relationship between the chip geometry, machining conditions and micrographs under different status.

II. Experimental Details

Machining operation was carried out on commercially available HDPE samples of dimension 15×75×150 mm. For the purpose of surface machining, a horizontal push-cut type shaper machine was used. The HSS single point V-shaped cutting tool was used, which had an angle of 60^{o}, clearance angle of 8˚and 0.8 mm notch radius. The depth of cut was varied from 0.5 to 4.0 mm (0.5, 1.0, 2.0, 4.0 mm), while the stroke per minute was 11, 48, 70 and 99 to maintain the cutting speed 3.0, 13.1, 19.4 and 27.5 m/min, respectively. The feed rate and stroke length was kept constant throughout the experiment at 0.254 mm/stroke and 165.0mm, respectively. The surface roughness (Center Line Average

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Roughness, Ra) was measured after each cut of the machined surface with a surface-roughness measuring instrument (Talysurf). Attempt was also made to measure the temperature of the machined surface during machining with the help of a non-contact laser gun. For each value of surface roughness, the average of ten readings has been taken. The hardness of the HDPE sample surfaces was measured using a Durometer Hardness tester. The chips generated during machining were photographed under as-received condition. Moreover, the micrographs of chip surfaces were also taken with the help of a USB microscope.

The experimental setup of shaper machine for machining of HDPE is illustrated in Fig. 1.

TABLE I
TOOL GEOMETRY AND CUTTING CONDITION

Tool nose radius (mm)	0.8
Back rake angle (°)	5
Clearance angle (°)	8
Feed rate (mm/stroke)	0.254
Depth of cut (mm)	0.5, 1.0, 2.0 and 4.0

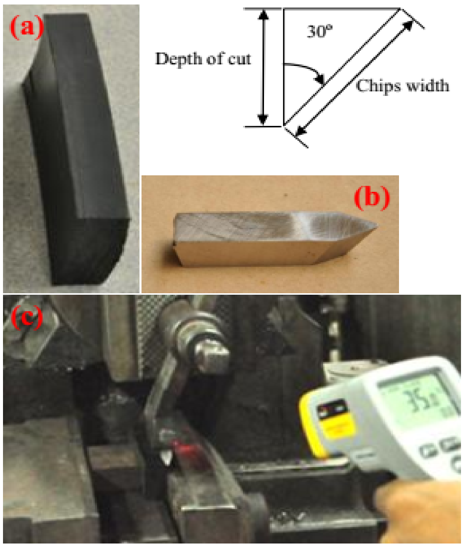

Fig. 1 (a) Experimental HDPE sample, (b) HSS cutting tool and (c) Experimental shaper machine

To estimate the deformation of chips at different direction, the following equations were used:

$$\text{Deformation along the direction of sample width, } \delta_w(\%) = \frac{\text{Chips width} - (\text{Depth of cut} \div \text{Cos } 30^{o})}{(\text{Depth of cut} \div \text{Cos } 30^{o})} \times 100 \quad (1)$$

$$\text{Deformation along the direction of sample thickness, } \delta_t(\%) = \frac{\text{Chips thickness} - \text{Feed}}{\text{Feed}} \times 100 \quad (2)$$

$$\text{Deformation along the direction of sample length, } \delta_l(\%) = \frac{\text{Chips length} - \text{Job length}}{\text{Job length}} \times 100 \quad (3)$$

III. RESULTS AND DISCUSSION

A. Surface Roughness

Fig. 2 shows the variation of surface roughness of the machined surfaces as a function of cutting speed at different depths of cut. In all the depths of cut, it is seen that the surface quality improves with higher cutting speed. At higher depth of cut, the improvement is more significant than that at lower depth of cut. This is probably because of the fact that higher cutting speed is associated with higher cutting temperature, which eventually causes softening of the work-piece material and then reducing the cutting forces and hence leading to better surface finish. The surface roughness could be improved by increasing cutting speed, though the improvement is very limited at higher cutting speed. Producing an enhanced surface finish at higher cutting speed is eminent in metal cutting. The conventional explanations are related to the formation of built-up-edge (BUE). In fact, the formation of BUE is favored in a certain range of cutting speed. By increasing cutting speed beyond this region, BUE is eliminated and thus the surface finish is improved. When the material shows less plasticity by increasing cutting speed and hence deformation velocity, the surface finish can be improved because of insignificant lateral plastic flow, which, in turn, causes less additional increase in the peak-to-valley height of the surface roughness. On the other hand, at lower cutting speeds, grooves are found to develop on the tool wear face. It is observed that, larger development of the grooves causes more significant deterioration of the surface finish. It is evident from Fig. 2 that the surface roughness increases with the increase of depth of cut, which is mainly due to the increase in thermal load and vibration on the machine tool. Furthermore, because of more contact area between the tool and work piece, high friction and tool wear exist, thereby leading to higher surface roughness. The optimum condition for obtaining maximum surface finish, with favorable rise in temperature at tool tip, is high cutting speed with low depth of cut [8].

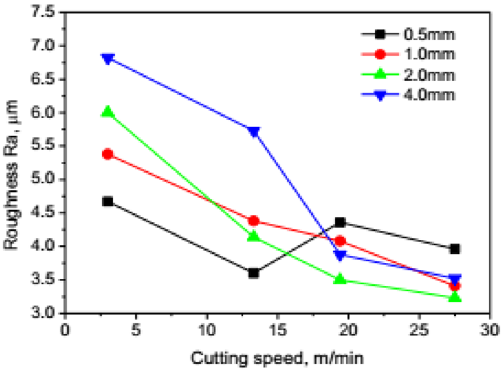

Fig. 2 Variation of surface roughness with cutting speed at different depth of cut

B. Temperature

The measured results of the surface temperature as a function of the cutting speed at different depths of cut are presented in Fig. 3. The results reflect the fact that the chip-tool interface temperature is closely connected to cutting speed. With the increase of cutting speed, friction increases, which induces an increase in temperature in the cutting zone. Further, with the increase of depth of cut, the chip section increases and thus friction of chip-tool increases, which eventually leads to an increase in temperature [9]. The effect of depth of cut on the temperature of the machined surface of HDPE samples is found to be clearly defined, especially at higher cutting speeds (see Fig. 3).

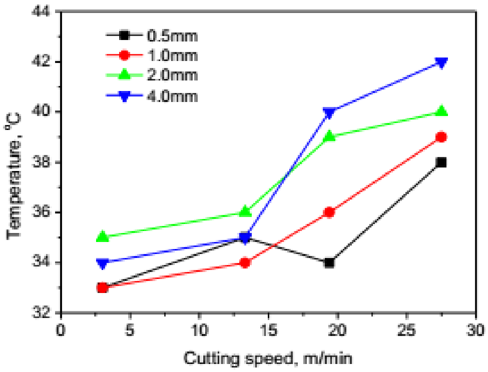

Fig. 3 Variation of surface temperature with cutting speed at different depth of cut a) 0.5 mm, b) 1.0 mm, c) 2.0 and d) 4.0 mm

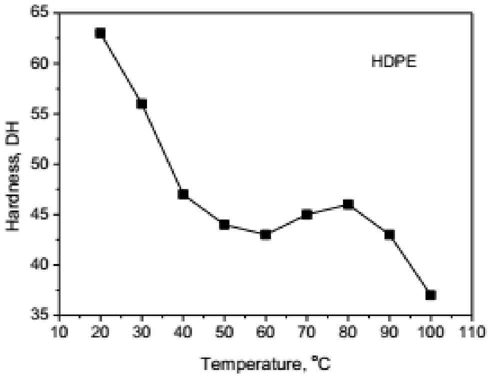

Fig. 4 Variation of hardness with real temperature

C. Hardness

In an attempt to investigate the role of temperature on the material hardness of HDPE, experiments were conducted to measure the surface hardness of the material under different temperatures, and the corresponding results are shown in Fig. 4. The results show that, with the increase temperature, the hardness of the material decreases. This is because of the fact that HDPE is an amorphous thermoplastic, in which the adjacent polymer chains associate through intermolecular forces, which weaken rapidly with increased temperature [10]. At the initial stage of temperature, the hardness drops sharply due to attain the glass transition point *Tg*. The hardness is found to remain more or less stable over a range of temperature around 50~80 °C, which is realized to be associated with the rubbery state of the material. Finally, a drop of hardness is again observed with a decreasing slope similar to that of the initial state and then reaches near about its melting state.

D. Chip Deformation

Figs. 5-7 describe the variation of normalized chip deformations along the directions of chips width (δ_w), thickness (δ_t) and length (δ_l), respectively, with respect to cutting speed at various depths of cut. The chip deformations along the three geometrical directions of the sample are obtained here in accordance with (1)-(3). It is observed that the deformations, in general, along the directions of width and length increase with the increase of cutting speed, but it shows a decreasing trend along the direction of thickness. The response for dept of cut is very pronoun for deformation along with thicknessof the chips. During the machining process, the workpiece material experiences the plastic deformation due to the interaction between the cutting tool surface and the chip. It has been realized that the workpiece material in the interior section of the chip undergoes plane strain deformation and flows perpendicular to the cutting edge, whereas the workpiece material close to the both sides experiences plane stress deformation and flows along the cutting edge due to the lack of transverse restriction. The ratio between the depth of cut and width of the chip undergoes plane strain deformation [10].

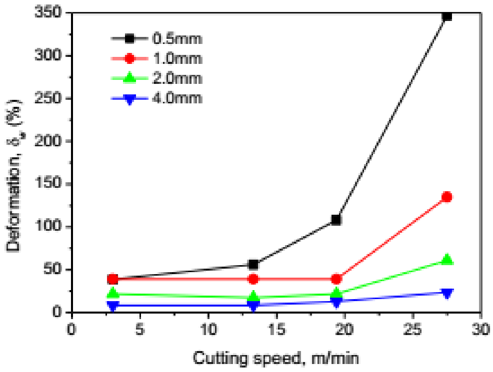

Fig. 5 Variation percentages of chips deformation along with the width with cutting speed at different depth of cut

In order to quantitively investigate the behavior of the side flow under different depth of cut in machining at different cutting speed is plotted as shown in Fig. 5. Due to the constant feed rate of experiments, the thickness deformation is varied with the depth of cut and cutting speed. It can be seen that the bigger ratio can prevent the plastic deformation along the cutting-edge direction, i.e. the side flow, to get the nearly uniform chip thickness as shown in Fig. 6. Asdecreasing the ratio, the restriction on the material to deform along the cutting-edge direction decreases. Besides that, the side flow as machining burrs was also observed on the machined surface. Based on these experimental results, it is proved that the plane strain assumption of the orthogonal cutting model is based on the appropriate width-to-thickness cutting ratio. The smaller ratio can cause more side flow on the machined chip and the machined surface [11]. Considering the fact that there is no traverse deformation in the middle of the chip due the symmetry, as shown in Fig. 7, it can be realized that the materials can be further deformed extensively under the machining conditions, and the chips with side flow always accompany the large maximum strains caused by the longitudinal negetive deformation [12].

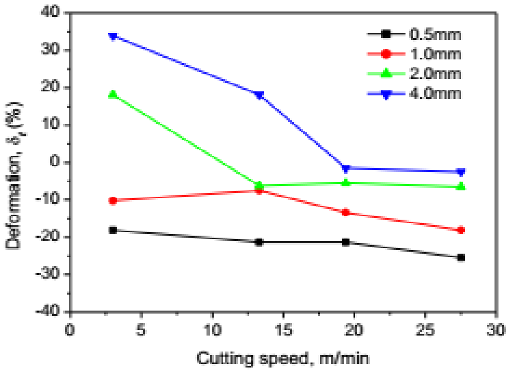

Fig. 6 Variation percentages of chips deformation along with the thickness with cutting speed at different depth of cut

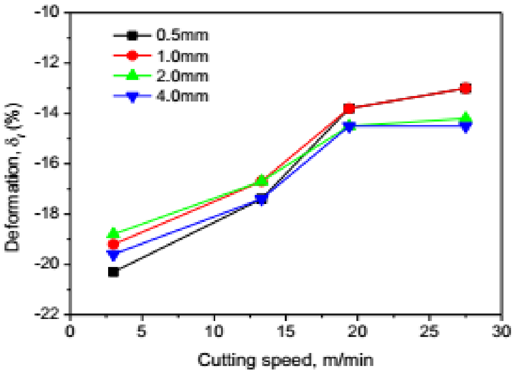

Fig. 7 Variation percentages of chips deformation along with the length with cutting speed at different depth of cut

E. Optical Micrographic Observation

The photo micrographs of the chips generated during machining of HDPE samples at different cutting speed and depths of cut are shown in Fig. 8. Chip curl radius was found to be related to the cutting speed for all depths of cut. Small curl radius was observed at low cutting speed, while with increasing cutting speed, chip curl radius was also increased gradually. With the increase of cutting speed, the shearing bands become more pronounced with a considerable reduction in the width of contact between the segments up to fragment. This may be attributed to the phenomenon of localized deformation in the primary shear zone that becomes more important with the increase in temperature. As a result, the mechanical properties of material degrade in the cutting zone by reducing resistance to plastic deformation, and thus cause sudden shearing of the chip by creating a plastic instability [13]. It would be worth mentioning that the geometrical parameters of the chip, *i.e.* the thickness and curl radius are related to the mechanism of heat dissipation from the chip section. With the decrease of chip thickness and increase in curl radius, the thermal effect will be diminished. The influence of heat on thick chips with small curl radii can be explained in different ways. For example, the thick chips with small curl radii have surface area comparatively less than those with small thickness and large curl radius, which, in turn, leads to less efficient heat dissipation, especially when the chips are in contact with the tool.

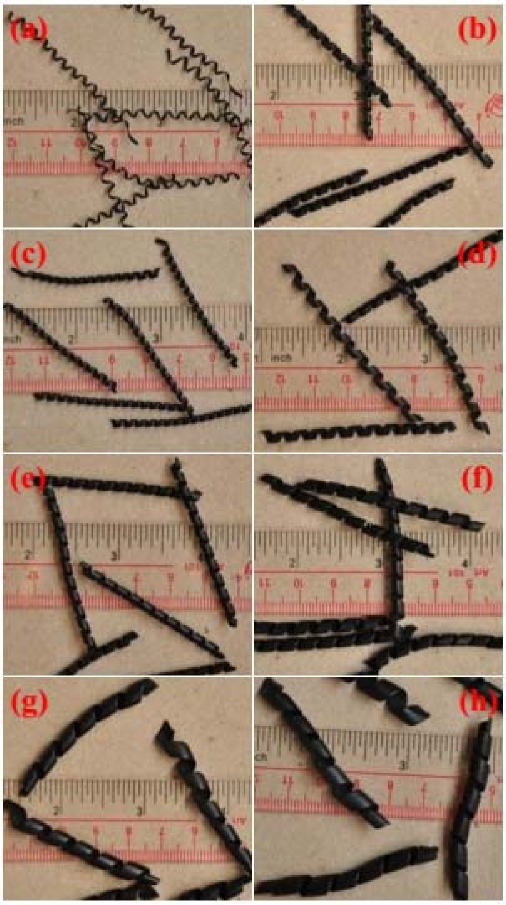

Fig. 8 Photo micrograph of the chips generated due to machining at different cutting speed and depth of cut (a) 3.0 m/min at 0.5 mm, (b) 27.5 m/min at 0.5 mm, (c) 3.0 m/min at 1.0mm, (d) 27.5 m/min at 1.0 mm, (e) 3.0 m/min at 2.0 mm, (f) 27.5 m/min at 2.0 mm, (g) 3.0 m/min at 4.0 mm and (h) 27.5 m/min at 4.0

Fig. 9 shows the plastically deformed regions on the chip surfaces and the shear deformation characteristics after machining obtained at different cutting speeds and depths of cut. At lower cutting speeds, the nature of chip surfaces is found to be very similar to that of relatively brittle material under different depths of cut. The areas created by crack propagation are evident on the micrographs. The initial fronts of crack propagation due to stress concentration may also be seen. These fronts indicate that the materials are hard and thus a higher magnitude of stress is needed to drive a crack to grow. At a small depth of cut and higher cutting speed, however, the cut surfaces of the material become different. Large crack propagation marks are rare on the surfaces but cracking can be still identified. The surfaces possess many small flat areas that have the features of tearing. No crack fronts as well as cracking can be identified in this case, and the modulus of the material seems very low. The observed surface characteristics strongly suggest that the temperature during machining of HDPE samples be larger than its *Tg*, and the material removal occur in the rubbery plateau region. Thus, a smooth surface of a polymeric material like, HDPE is difficult to obtain due to its high brittleness below *Tg* and rubber-like behavior above *Tg* [7].

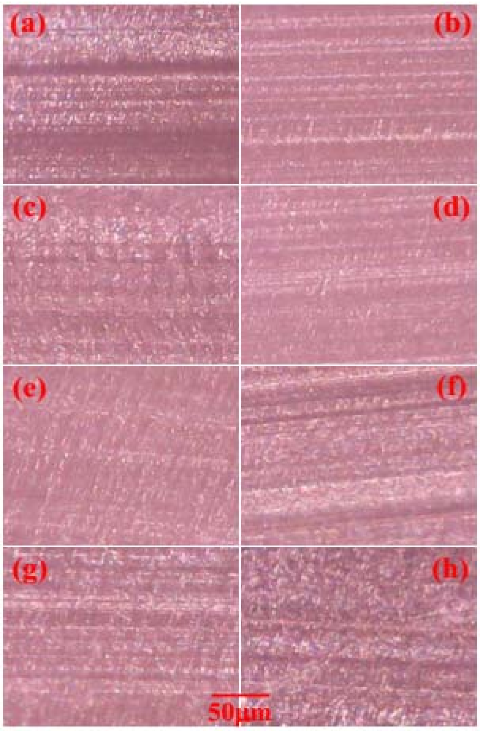

Fig. 9 Optical microstructure of the chips surface generated due to machining at different cutting speed and depth of cut (a) 3.0 m/min at 0.5 mm, (b) 27.5 m/min at 0.5 mm, (c) 3.0 m/min at 1.0 mm, (d) 27.5 m/min at 1.0 mm, (e) 3.0 m/min at 2.0 mm, (f) 27.5 m/min at 2.0 mm, (g) 3.0 m/min at 4.0 mm and (h) 27.5 m/min at 4.0 mm

IV. CONCLUSION

The major machining parameters, like cutting speed and depth of cut are found to have influential effect on the formation of chips from HDPE samples. Surface roughness decreases with the increase of cutting speed due to the presence of built-up-edge at lower cutting speeds. Continuous chips are encountered for all the cutting conditions investigated for HDPE samples. Chips width increases but the thickness decreases with the increase of cutting speed, which is not that prominent for the case of dept of cut. The length of chips is found to be always smaller than the corresponding job length, and this discrepancy becomes more prominent for the case of lower cutting speeds. The results of the investigation also show that the chip thickness tends to decrease with the decrease of cutting speed. However, an increase in cutting speed generally causes the force component to decrease, which is eventually attributed to the formation of chips with a thinner thickness. HDPE weaken rapidly with increased temperature as it is amorphous thermoplastic. Microstructures of the chips reveal that cracks are formed at high cutting speeds and high depths of cut, but fewer cracks are observed at high speed and low depth of cut.

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