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Design of Polypropylene Random Co-Polymer Pipe Cutter

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Abstract:- The purpose of this research is to design disc cutter for cutting poly propylene random co-polymer (PPR) and high density polypropylene (HDP) extrudates. Analytical methods and software including like Catia and ANSYS are used to design the tool and analyze the effect of load on the cutter. In designing the disc Cutter, using the digital logic method of material selection, the optimum material, carbon steel 19573 with the least cost, locally obtainable, manufacturable and with hardness 63.42HRC is selected. The desired optimum combination of hardness and toughness of the cutter is obtained using hardening temperature 1020^0C, tempering temperature 200^0C, and tempering time 120min which finally gives a hardness value of 63.42HRC. The strength and quality of cut edge are tested by cutting hard plastic PPR pipe with maximum thickness of 12.9mm. By the same setup of the cutter used in the factory the prototype disc cutter serves and its failure rate improves from cutting 150 to 250 PPR pipe pieces which was recognized by the industry. The research results can be used to design the cutter disk and fabricate a cutter with enough strength to cut different thickness of PPR pipes without breakage, reducing unwanted additional cost.

Keywords:- *Disc Cutter, Bevel Angle, Tool Stress, Hardness, and Tool Contact Area.*

I. INTRODUCTION

Disc cutters are a group of cutting tools which are used for cutting a variety of materials such as metal alloys, ceramics, plastics, etc. In using the disc cutters for cutting HDP and PPR pipes to the desired length the kerf produced will affect the dimension of the final product.

The kerf size is dependent on the thickness of the disc cutters. The thicker the thickness of the cutter the larger the kerf size and the material wastage and also creates a lot of friction that develops high temperature at the point of cutting and can lead to undesirable changes in structure and color of the material. In order to prevent this, it is advisable to use the disc cutter as thin as possible so that the product wouldn't get warmed up leading to disc failure. However reduction of the thickness of the cutters for cutting harder materials such as harder and thicker PPR plastics also leads to failure. In the case industry a frequent failure of the disc cutters is observed after cutting an average 100 pieces of PPR pipes with diameter 50mm and thickness 9.3mm and above. The purpose of this research is to design disc cutter for cutting poly propylene random co- polymer (PPR) and high density polypropylene (HDP) extrudates which prevent early failure.

Analytical and experimental methods are employed for the study. The stress analysis conducted analytically is validated by finite element method. As applied the reverse engineering it is important to select the workable dimensions of PPR pipes and tools under investigations. Data of the chemical composition and hardness of the sample specimens are collected from HDP and PPR cutter using spectrometry and Rockwell hardness tester. It is found that the alloying elements and cutter hardness are carbon tool steel and hardness of 60.0HRC. The sample dimensions of the extruded pipe are selected based on the frequently produced standard PPR tubes with diameter of □ 50mm and thickness 9.3mm where the cutter diameter □ 60mm, cutting edge with 7.5mm height.

II. THEORETICAL BACKGROUND

The major factors which affect tool life are machining variable such as cutting speed, feed & depth of cut, the work material being machined, tool material, tool geometry, coolant application and some unknown factors like vibration, & rigidity of machine tool etc. [1]. In designing the tool with due consideration of these factors, the tool became wear resistant so that it maintains its cutting edge for a reasonable length of time and should be tough without compromising its strength. High wear resistance, high resistance to the softening effect of heat, and good toughness are requirements for effective use in industrial cutting operations. Material selection for cutting tool depends on the hardness of material to be cut. For plastic material carbon steel and high speed steel (HSS) are meeting the requirements [2].

A. Tool Angles

The correct tool design leads to predictable conditions during the process with impact on fundamental aspects of manufacturing and equipment. An optimal blade angle is one of the most important requirements to minimize the plastic flow of the edge region without affecting the sharpness [3].

A wedge functions by converting a force applied to its blunt end into forces perpendicular (normal) to its inclined surfaces [4]. Although a short wedge with a wide angle may do a job faster, it requires more force than a long wedge with a narrow angle. For increased durability of the wedge the critical blade angle in terms of abrasion/breakage of the blade should be 28 degrees [5]. The sharpness of a blade is a key parameter in cutting soft solids [6].

The blade angle (Figure 1) is the angle at which the surfaces of the edge or their respective tangent planes intersect and the force is proportional to the tangent of the blade angle or (*F*□□)

[7]. An optimal blade angle is one of the most important requirements to minimize the plastic flow of the edge region without affecting the sharpness. Another factor of interest here is the effect of the final edge angle, 2β, upon sharpening characteristics.

The sharpness of a blade is a key parameter in cutting polymer materials. It has a first order effect on the effort and hence energy needed to cut, the quality of the cut surface and the life of the cutting instrument [7].

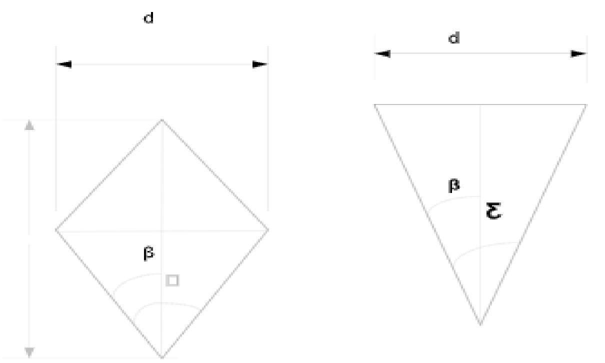

Fig 1:- Rhombic and a triangular blade cross-section [8].

Where; b is width, d is thickness and the edge ang

It is examined [9] that the relations for the edge angle of a double-edged blade and the single- edged blade with the blade thickness d and width b as shown in equation (1).

$$\tan\frac{\delta}{2} = \frac{d}{b} \quad and \quad \tan\frac{\varepsilon}{2} = \frac{d}{2b} \qquad \ldots (1)$$

The relation of b and d of crusher blade is $b \leq d$ and for blades with a slim profile $b \geq d$.

B. Material Properties

It is very important to enhance the material properties especially fatigue strength and fracture toughness to increase the life of the tools and decreasing the production cost. The effect of heat treatment on fatigue and fracture of various tools steel is high and sharpness of cutter is a key parameter in cutting tools, by selecting appropriate material it is possible to get desired property of cutter. Various heat treatments like hardening, tempering and cryogenic treatments are used to increase the wear resistance and the mechanical properties of the tool steels [10]. Heat treatments of tool steels enhance the cutting properties of the tool. After hardening of tool steel tempering should be followed to remove some of the brittleness [11]. The resulting strength, hardness, and ductility depend on the temperature to which the steel is heated during the tempering process.

So it can be concluded that an incorrect tool design leads to unpredictable condition during the cutting process.

III. RESULTS AND DISCUSSIONS

A. Determination of contact area of Disk Cutter with PPR Pipe

When a cutter is in cutting process of the pipe □ *1* mm whose thickness T mm, with the disk cutter □ *2* mm, cutting edge with h mm, height, being fully imbedded in to the PPR tube, cuts the remaining T-h mm part of the pipe thickness. To determine the stress developed in the cutter, the contact surface area of the cutter and the material to be cut is important. During cutting process, the pipe and the Disk cutter will intersect forming an elliptical contact region. The disk cutter imbedded in to the pipe during cutting process. At the end of cut condition, where the cutting edge is fully imbedded, the disk cutter and pipe contact region form an elliptical shape with minor diameter which equals to the edge length of disk cutter, and line LM major diameter of formed contact elliptical region as illustrated in Figure 2.

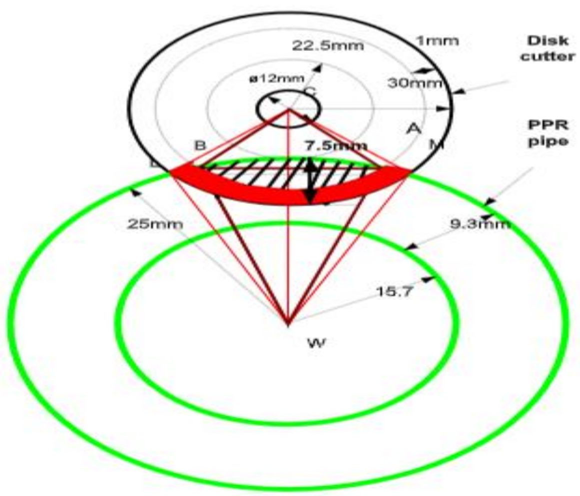

Fig 2:- Cross sectional view of pipe and disk cutter contact during cutting process.

Referring to figure 2, Area of contact region and the distance between pipe and cutter center is determined by (2) and (3) respectively.

Area of contact regions=Area of polygon CLWM-Area of disc cutter sector CLM-Area of pipe sector WLM ...(2)

$$\overline{CW} = R_P + R_B \,□ E_L \qquad \ldots (3)$$

Where; R_p is radius of pipe, R_B is radius of blade. E_L is cutter edge length; CW is the distance of pipe and cutter center.

Accordingly using the figure 2 trigonometrically relationship it is found for cutting pipe diameter of 50mm the contact region area is129.6mm^2 which includes primary and secondary edge of the cutter. Taking additional polygon CBWA the Primary edge contact area equals the area difference of contact region of cutter and secondary edge contact area.

The Primary edge contact area (A1) is 15.2mm^2 inclined at angle of 7.125^0 and the secondary edge contact area is 114.4 mm^2 inclined at 4.18^0 on each side of the cutter disk as shown in the figure 3 below.

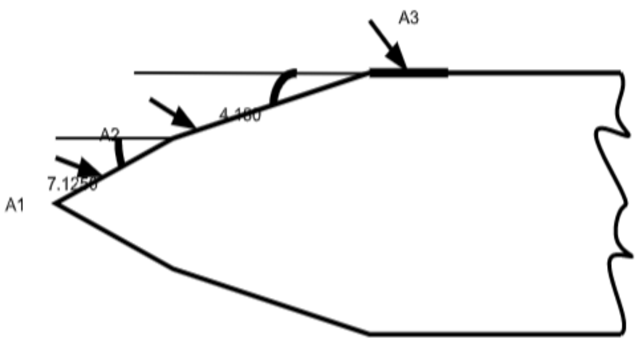

Fig 3:- Cutter cutting edge and pipe contact area with its angle of inclination.

These calculated areas are different during cutting of different pipe thickness using different disk cutters. So, different stress value are obtained as the area is varied even the applied force is constant. Accordingly the contact area of designed disk cutter has the following values (Table 1)

Cutting Edges	In cutting pipe diameter 50mm	In cutting pipe diameter 75mm
Area of primary edge (A1), mm^2	72	240
Area of secondary edge (A2), mm^2	130.5	113

Table 1:- Area of cutting edges of disc cutter

B. The load distribution on the cutter

The mechanical advantage (MA) of a tool is depicted from the general relation where the ratio of the load i.e. the resistance overcomes by a machine, FB to the force applied FA. It can also be calculated by dividing the length of the slope by the wedge's width as given by (4).

$$MA = \frac{F_B}{F_A} = \frac{1}{\tan\alpha} = \frac{l}{w} \quad \ldots(4)$$

The more acute, or narrow, the angle of a wedge, the greater the ratio of the length of its slope to its width, and thus the more mechanical advantage it will yield. Thus, the smaller the angle α, the greater the ratio of the splitting force to the applied force on the wedge. This relation for mechanical advantage applies to cutting edges of the disc plastic cutters. Figure 4 shows that the load distribution on wedge (cutting edge) due to applied force during splitting of parts.

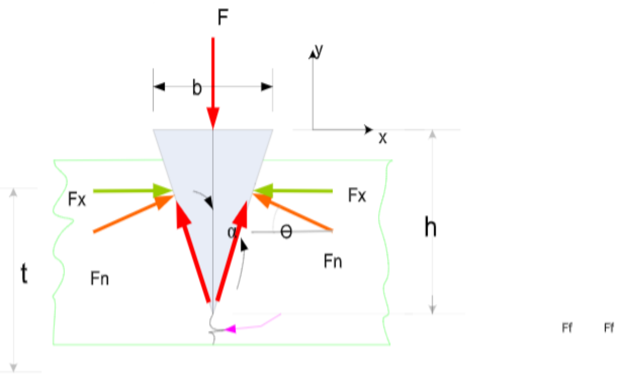

Fig 4:- Load distribution due to load applied on the wedge

Where; F is the vertically applied cutting force, b is thickness of wedge, Fn is force normal to edge of wedge, Ff is friction force between wedge and cut part, Fx is horizontal force to depart the cut material, *t* is thickness of the material to be cut, *h* is length of the wedge and □ is half of the wedge angle.

Because of symmetry, the same variables, Fn and Ff, are used on both the right side and left side of the wedge. The cross-section of a splitting wedge with its length oriented vertically. A downward force produces forces perpendicular to its inclined surfaces in which the wedge angle.

$$\alpha = \tan^{-1}\left(\frac{b}{2h}\right) \quad \ldots(5)$$

For motion of cutter to be impending in to the work (pipe) during cutting, the vertical component of the friction forces and normal forces acting on the wedge of cutter must be equal to the applied force [9].

During cutting process, cutting force is tangent to disk cutter and the applied force is distributed along the cutting edge of cutter as shown in the figure 5 below.

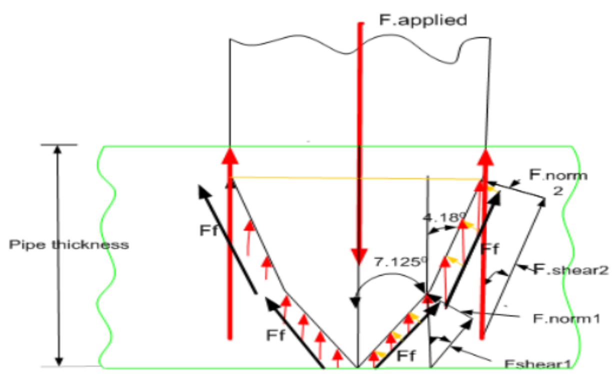

Fig 5:- Load distribution on the cutter (blade) during cutting

Based on the force component, F_y, of the cutting machine it is found that the magnitude of the force by which the cutter advance to cut the extrudate is = F_f =728N.

Hence the applied force 728N force has different values on the two regions (primary edge A_1 and secondary edge A_2).due to different mechanical advantage of its wedge action.

C. Friction and sheer force

The movement of blade in to the pipe during cutting is opposed by fiction force between the blade edge and the pipe. Coefficient of friction between steel and plastic ranges from 0.1 to 0.3.Then the frictional force (6),

$$F_f = F_n \mu = 0.2F_n \quad \ldots (6)$$

Where the normal force F_n is calculated considering the value of F_f and equals 1129N. Accordingly **Friction force on the blade is** 225.8N.

The sheer force (7) then will be

$$F_{shear} = \frac{F_n}{\tan 7.125} = \frac{1129N}{\tan 7.125} = 9032\,N \quad \ldots (7)$$

D. Stress calculation of blade

The blade has primary edge and secondary edge which have its own advantage during slitting (cutting) process. These regions have different thickness and contact area. So, different stress value can be observed in each region. Region 1(primary edge) is critical area of blade where the thickness is much less than the other part to carry the high force.

The force 1129N and normal to the edge surface is distributed on area. During this condition the cutter will be stressed, and can be calculated.

Stress on primary cutting edge, during cutting a range of 50mm to 75mm pipes with existing disk cutter with ultimate strength 620.5Mpa is calculated. The cross section areas A of the disc cutter under consideration is A_1= 240 mm^2.

The Normal stress, sheer stress and Von-Mises stress are calculated using equation (8), (9) and (10).

$$\sigma = \frac{F_n}{A} \quad \ldots (8)$$

$$\tau_{xy} = \frac{F_{shear}}{A} \quad \ldots (9)$$

$$\sigma_v = \sqrt{\sigma^2 + 3\tau_{xy}^2} \quad \ldots (10)$$

Accordingly these stresses for cross section area 240mm^2 are found 5.04MPa, 40.32 MPa and 70.02 MPa respectively. For the given cross section the stress values are within acceptable stress values of the tool.

E. Material selection

The optimum and cost effective material for the disc cutter is selected using the digital logic method. Factors such as hardness, manufacturability, cost, toughness and availability are used in the digital logic material selection method. According to this method, material 19573 is ranked first for disc cutter manufacturing and its chemical composition is depicted in table 2.

The optimum hardness value is obtained using hardening temperature 1020^{0}C, tempering temperature 200^{0}C, and tempering time 120min which finally gives a hardness value of 63.42HRC.

Expected composition	**C**	**Si**	**Mn**	**P**	**S**	**Cr**	**Mo**	**V**
Min. %	1.45	0.10	0.20	--	--	11.00	0.70	0.7
Max. %	1.60	0.60	0.60	0.030	0.030	13.00	1.00	1.00
Obtained	1.45	0.44	0.42	0.055	0.11	10.71	0.63	--

Table 2:- The chemical composition of candidate material (carbon steel 19573).

The major dimensions of the disc cutter are presented in table 3 as follows.

Outer diameter	**Inner diameter**	**thickness**	**Primary cutting edge angle**	**Secondary cutting edge angle**	**Height of 1st cutting angle**	**Height of 2nd cutting angle**
60mm	12mm	2.73mm	4.18˚C	14.5 ˚C	16mm	10mm

Table 3:- The major dimensions of the disc cutter

IV. FINITE ELEMENT ANALYSIS (FEA) OF DISK CUTTER

The objectives of the finite element method are to establish the potential failure modes and to achieve the optimal design of the geometry being modeled. In this study, FEA ANSYS 15.0 software package is used to find the stresses and strains developed in cutting disk under load during cutting process.

The FEA tool is used as the pre-processing and post-processing purpose. The pre-processing includes building the geometric model by importing the disk cutter and generating mesh, giving the correct material properties, and setting loading conditions. Therefore, the Geometry has been modeled using CATIA V5R19 and then imported to ANSYS software.

Specifying boundary conditions at the center, where the bolt is inserted to disk cutter hole, during fastening it to the holder. The disk cutter is not rotating about the center of the bolt during cutting process rather revolve planetary around the pipe. So, the edge of the hole is taken as fixed part of the disk cutter.

The force applied to the cutter disk through its holder which is 728N in magnitude is applied at the hole and down ward direction (figure 6 a) and the pipe resistance force is directed opposite to the applied force (figure 6 b). During cutting, the cutter revolves planetary around the pipe, due to this rotation tangential cutting force is used to cut the pipe (figure 6 c).

Finally, the solution, the equivalent (von-Mises) stress is observed as shown in figure 6d bellow.

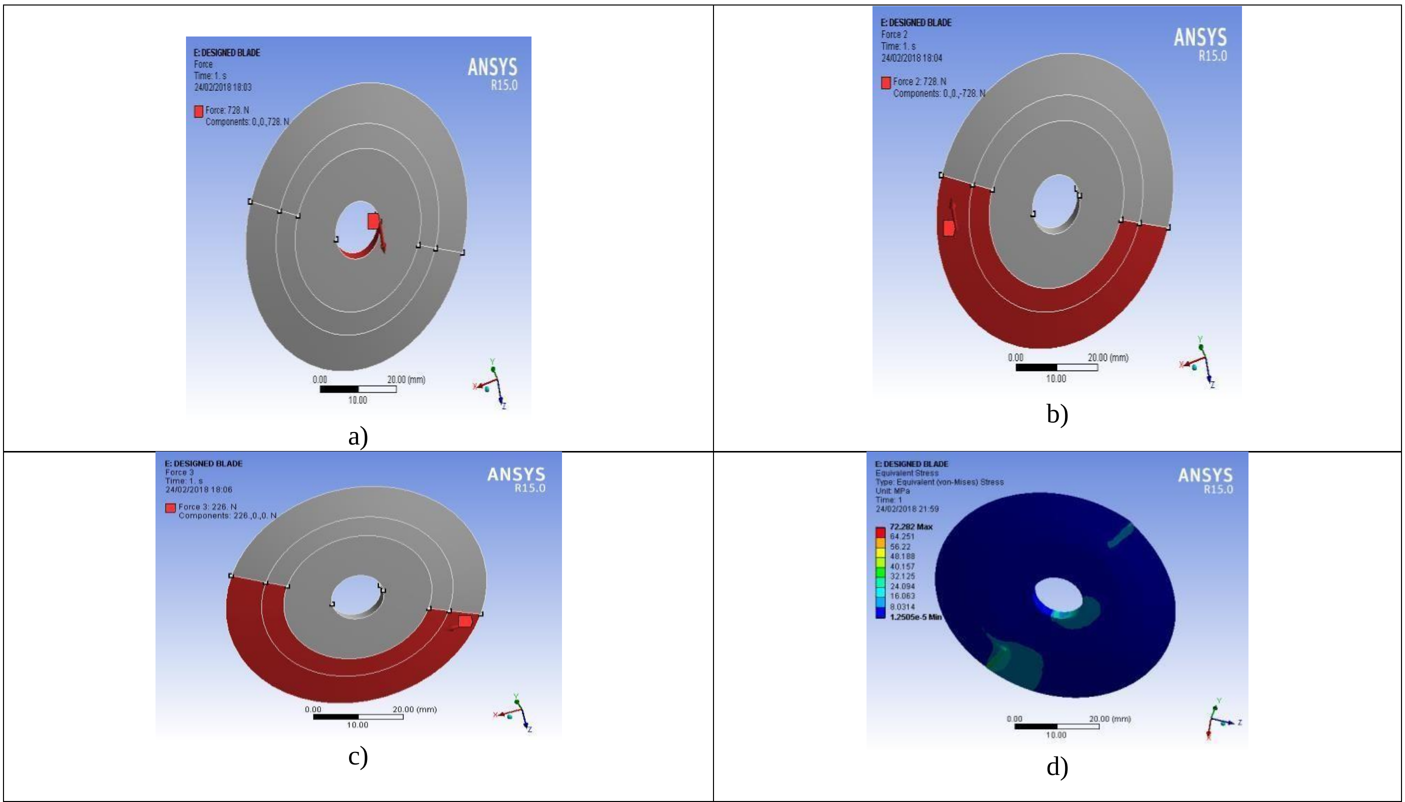

Figure 6: a) The force applied to the cutter disk through its holder b) force resisting by the PPR pipe during cutting c) cutting force tangent to the cutter disk, d) the von-misses stress on the disk cutter.

Based on the analyses the maximum Von Mises stress is found 72.282MPa. This result is for the pipe diameter 75mm of thickness 12.9mm (which is the largest thickness of the pipe produced). It is believed that if the cutter is designed for the largest thickness, it can cut the standard PPR pipes with less thickness with diameter 50mm and 65mm.

The percent error (%E) which is the difference between analytical value and Ansys results is 3.13% which is acceptable for the given design.

V. CONCLUSIONS

Based on the design carried out and test of the prototype the following main conclusions of the study can be presented.

The major reason for a tool failure is found to be its incompatibility with the hardness and thickness of the PPR tube. As the thickness of the pipe increased the disc cutter became stressed and could not with stand the feed force.

To design the disc cutter with improved geometry and tool material the sample tool material composition and property was analyzed using spectrometer and Rockwell hardness tester and found the alloying elements and cutter hardness of carbon tool steel and hardness of 60.0HRC. By using the digital logic method of material selection carbon steel 19573 with hardness 63.42HRC is selected as optimum material for the cutter which is easily available, less cost and manufacturable. The tool design included the working angles such as edge angle 14.25^0 and clearance angle 4.18^0 for long life service of the cutter.

The disc cutter is designed by increasing the thickness from 1.2mm to 2.73mm. To provide the required optimum hardness and toughness it was heat treated with the temperature of 1020^0C, tempering temperature 200^0C, and tempering time 120min which finally gives a hardness value of 63.42HRC. The strength and quality of cut edge are tested by cutting hard plastic PPR pipe with maximum thickness of 12.9mm. By the same setup of the cutter used in the factory the prototype disc cutter serves without failure up to cutting 250 pieces which was recognized by the industry.

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