Management Science and Engineering ***ISSN 1913-0341*** *Vol.3 No.4 2009*
Canadian Research & Development Center of Sciences and Cultures *12/20/2009*
Http://www.cscanada.org Http://www.cscanada.net
E-mail: cscanada.mse@gmail.com; caooc@hotmail.com

Curling Behavior of Circular Metal Tubes

Mohd Rozaiman Aziz[1]
Roslan Ahmad[2]
Kamaruzaman Jusoff[3]

Abstract: An energy absorber device is a device that is capable to convert one form of energy to the plastic deformation or another form of energy. Plastic deformation energy can be converted into several modes of deformation including axial crushing, inversion, splitting, lateral indentation and lateral flattening. The objective of this paper was to investigate the axial splitting and curling behavior of aluminium circular metal tubes which was compressed axially under static loading. An experimental investigation was carried out by using three types of dies with different semi-angles, α which was 45^0, 60^0 and 75^0. To ease the splitting process, the tube was introduced with 4 and 6 slits with the length of 5 mm at the leading edge of the tube. The slit prevented the tubes from buckling and established the split and curl mode during the compression process. The result showed that for a specimen with 4 initial saw cuts, the number of slits remained except for semi angle die of 60^0 where it branched into 6 splits. Meanwhile for a specimen with 6 initial saw cuts, the effect of semi angle die was insignificant where the number of slits remained the same after compression. The mean load was found proportional to the semi angle die. In conclusion, the axial splitting and curling of aluminium circular metal tubes has high potential as an energy absorber.
Keywords: axial loading; curling; deformation; semi-angles; slits

1. INTRODUCTION

Splitting mode of deformation is a special case of tube inversion where the die radius is large enough to

[1] Faculty of Mechanical Engineering, Universiti Teknologi MARA Malaysia,13500. Permatang Pauh, Pulau Pinang, Malaysia.
E-mail: man@ppinang.uitm.edu.my
[2] School of Mechanics Engineering,Universiti Sains Malaysia,Kampus Kejuruteraan Seri Ampangan,14300 Seberang Perai Selatan, Pulau Pinang, Malaysia.
E-mail: roslan@eng.usm.my
[3] Faculty of Forestry,Universiti Putra Malaysia,43400 Serdang, Selangor, Malaysia.
E-mail: kjusof@yahoo.com
* Received 11 October 2009; accepted 14 November 2009

cause splitting instead of inversion. Stronge et al (1983) conducted a study of square aluminium that pressed over die where the square aluminium tubes were splits at corners and curls outwards in quasi-static loading. An experiment on the effect of die radius showed that a remarkably constant force causes rate independent deformation in tubes. Stronge et al (1983) suggested that square aluminium tubes, which experienced both split and curled conditions, could be designed for energy absorbing systems. On the other hand, Reddy and Reid (1986) investigated the tube splitting of aluminium and mild steel tubes compressed onto die radius of 4 mm, 6 mm and 10 mm under quasi-static loading. From this research, Reddy and Reid (1986) concluded that compared with axial loading and tube inversion, the operating load for tube splitting was lower. The advantages of tube splitting were the flat load deflection characteristics and that it can be operated successfully with a wide range of the tube properties and die geometries, that can't be achieved together by axial loading and tube inversion under similar loading condition.

Hong-Wei et al (2000) studied the dynamic axial impact characteristics and energy absorption efficiency of composite externally wrapped metal tubes. From the experiment conducted, four main collapse modes were identified, which were compound diamond, compound fragmentation, delamination and catastrophic failure. These collapses were an effective indicator of energy absorption mechanism and efficiency. Huang et al (2002) carried-out study into energy absorbing behavior of axially splitting square metal tubes under quasi-static loading. The observation obtained was in energy dissipating system, whereby there were three components i.e. tearing energy, plastic deformation and frictional energy. On top of that, Huang et al (2002) stated that tubes that are both split and curl may be used as efficient, by increased the stroke energy absorbing devices, much related to the claim made by Stronge et al (1983). Meanwhile, Lu and Wang (2002) investigated the energy absorption of square tube pierced under quasi-static loading. The wall thickness of tubes was 1.6 and 2.5 mm and the length were varied. Lu and Wang (2002) found that when the wall thickness increased, the maximum load became higher for all the modes of failure.

Zou and Reid (2005) studied the behavior of wavy-edged fracture in axially aluminium tubes. From their brief investigation, they suggested that the wavy edge on the wreckage of the fuselage skin was caused by transverse load, most likely due to internal explosion. In another study by Haipeng et al (2007) who carried-out numerical study of hybrid pultruded and $\pm 45^o$ braided tubes under axial crushing. Both quasi-static compression and axial dynamic impact loadings were employed. Haipeng et al (2007) concluded that the pultruded tube had the highest stiffness and magnitude of energy absorption capacity among the tubes considered.The characteristics of spot-welded thin-walled composite steel carbon fibre-reinforced polymer (CFRP) square tubes under static and dynamic axial crushing had also been investigated by Bambach et al (2009). They observed that the use of externally bonded CFRP to spot-welded steel square hollow section may increased the mean crush load and specific energy by up to 3.33 and 2.35 times, respectively under static loading. Meanwhile under dynamic loading, the mean crush load and specific energy was up to 1.84 and 1.59 times, respectively.

Therefore, the objective of this study was to investigate the effect of the number of slits and semi-angle die whereby the energy absorbing capabilities are influenced by these factors.

2. METHODS

2.1 Specimen and Die Preparation

Initial preparation for the specimen in tube splitting such as cutting, end turning and stress relief were involved. The length of aluminium tube was chosen as 200 mm since a larger stroke is needed for the tube to split and slide along the die. For tube splitting, die with three different semi-angles, α that is 45^0, 60^0 and 75^0 was employed. The die was made of mild steel. Schematic drawing of die with semi-angle of 45^0 is shown in Figure 1 and photograph of actual dies used in the experiment is presented in Figure 2. Figure 3 shows the flow chart of the specimen and die preparation for tube splitting.

Typical applied force–displacement traces for three different cases (α = 45°, 60° and 75°) for 4 and 6 initial slits are shown in Figures 4 and 5, respectively. In each case, the force initially increased linearly to a peak, which corresponded to initiation of 4 or 6 cracks. After that, the load decreased rapidly as the cracks propagated along the tube by ductile tearing. The splitting sides then began to roll into curls. With increasing plastic deformation, the load again increased. Eventually, the curls formed with a constant radius as the plastic bending and load had reached a steady state. Similar pattern of applied force-compression curve was observed by Huang et al (2002) as shown in Figure 6.

The peak load is tabulated in Table 1. In the case of 4 slits, the peak load increased as the semi-angle changed from 45^0 to 75^0. The same pattern was observed when a die with 6 slits was employed. It can be concluded that the peak load increased when the die becomes steeper. It was because in order to start the bending, stretching and tearing process, a higher load was required for a steeper die compared to a less steep die. It was believed that if the tube has been pre-formed, the peak load will become less. The finding of this study is also backed up by Huang et al (2002) who confirmed similar result.

2.2Modes of Deformation

Figures 7 and 8 show the modes of deformation for both tubes with 4 and 6 initial slits, respectively after compression. At the beginning of the compression process, the strips between initial slits buckled and flared as guided by the respective die, which led to the circumferential stretching of the tube. After a certain level has been reached, cracks occur at some initial slits locations and they were propagated along the axial due to continuous ductile tearing. Strips were formed as cracks roll up into curls due to the strips ends which were free to bend themselves. Then, after these curls have completed one revolution, the front edges of the curls contacted the tube of the wall. Even though initially a number of 4 slits were introduced to initiate the split, eventually the split increases in number. For 45^0 die, the number of split remained 4 after the compression, whereas the 60^0 die resulted in a number of 6 splits instead of 4 splits. The 75^0 die resulted in a number of 4 splits with slight tearing and merging of the cracks.

For a specimen with 6 initial slits, the number of slits remained the same as the deformation progressed. There was no merging or branching that took place when compressed on die with the semi angle of 45° and 60°. The type of failure mode observed with respect to the number of slit and semi angle die is summarized in Table 2. Similar observation was also observed by Huang et al (2002) when testing mild steel tubes with 8 slits. Their specimen as in Figure 9 also experienced merging or branching.

3. CONCLUSION

The introduction of slit to the specimen was necessary to initiate slitting rather than inversion. The load-displacement curve initially increased linearly to a peak, which corresponded to the initiation of cracks and then decreased rapidly as the cracks propagated along the tube by ductile tearing. The mode of deformation involves the process of bending, stretching, tearing and curling or rolling. For a specimen with 4 initial saw cuts, the number of slits remained except for semi angle die of 60^0 where it branched into 6 splits. For a specimen with 6 initial saw cuts, the effect of semi angle die was insignificant where the number of slits remain the same after compression. The mean load was proportional to the semi angle die.

REFERENCES

Alghamdi。 (2001). Collapsible impact energy absorbers: an overview. *Thin-Walled Structures;* 39: 189-213.

Atkins, A.G. (1987). On the numbers of cracks in the axial splitting ductile metal tubes. *International Journal of Mechanical Sciences;* 29-2: 115-121.

Bambach, M.R., Jama, H.H. and Elchalakani, M. (2009). Static and dynamic axial crushing of spot-welded composite steel-CFRP square tubes. *International Journal of Impact Engineering*; 36: 1083-1094

Haipeng Han, Farid Taheri, Neil Pegg and You Lu (2007). A numerical study on the axial crushing response of hybrid pultruded and ± 45^o braided tubes. *Composite Structures*; 80: 253-264

Hong-Wei Song, Zhi-Min Wan, Zhi-Wan Xie and Xing-Wen Du (2000). Axial impact behavior and energy absorption efficiency of composite wrapped metal tubes. *International Journal of Impact Engineering;* 24: 385-401

Huang, X., Lu, G., and Yu, T.X. (2002). On the axial splitting and curling of circular metal tubes. *International Journal of Mechanical Sciences;* 44: 2369-2391.

Lu, G., Ong, L.S., Wang, B. and Ng, H.W. (1994). An experimental study on tearing energy in splitting square metal tubes. *International Journal of Mechanical Sciences*; 36-12: 1087-1097.

Lu, G. and Wang, X. (2002). On the quasi-static piercing of square metal tubes. *International Journal of Mechanical Sciences*; 44: 1101-1115.

Mamalis, A.G., Manolakos, D.E., Demosthenous, A.G. and Ioannidis, M.B. (1997). Experimental determination of splitting in axially collapsed thick-walled fibre-reinforced composite frusta. *Thin-Walled Structures;* 28: 279-296.

Reddy, T.Y. and Reid, S.R. (1986). Axial splitting of circular metal tubes. *International Journal of Mechanical Sciences;* 28-2: 111-131.

Reid, S.R. (1993). Plastic deformation mechanisms in axially compressed metal tubes used as impact energy absorbers. *International Journal of Mechanical Sciences;* 35-12: 1035-1052.

Stronge, W.J., Yu, T.X. and Johnson, W. (1983). Long stroke energy dissipation in splitting tubes. *International Journal of Mechanical Sciences;* 25-9~10: 637-647.

Mamalis, A.G., Manolakos, D.E., Demosthenous, A.G. and Ioannidis, M.B. (1997). Experimental determination of splitting in axially collapsed thick-walled fibre-reinforced composite frusta. *Thin-Walled Structures;* 28: 279-296.

Reddy, T.Y. and Reid, S.R. (1986). Axial splitting of circular metal tubes. *International Journal of Mechanical Sciences;* 28-2: 111-131.

Reid, S.R. (1993). Plastic deformation mechanisms in axially compressed metal tubes used as impact energy absorbers. *International Journal of Mechanical Sciences;* 35-12: 1035-1052.

Stronge, W.J., Yu, T.X. and Johnson, W. (1983). Long stroke energy dissipation in splitting tubes. *International Journal of Mechanical Sciences.;* 25-9~10: 637-647.

Zou, Z. and Reid, S.R. (2005). Wavy-edged fractures in axially split aluminium tubes. *International Journal of Solids and Structures*; 42: 4519-4540.

FIGURES

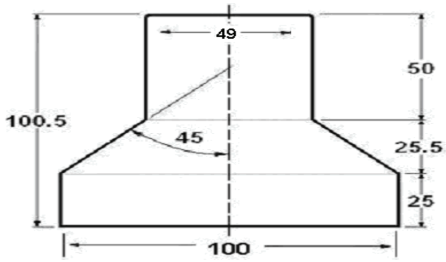
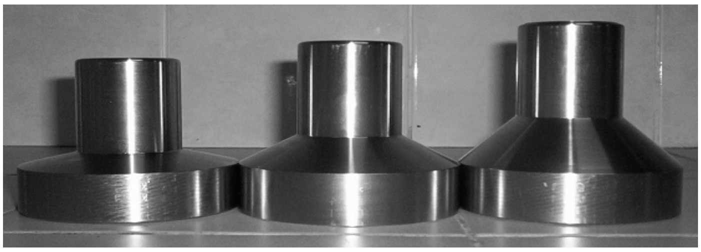


Figure 1: Schematic Diagram of Splitting Die for 45^0 Semi-angle



(a) (b) (c)

Figure 2: Photograph of Splitting Die; (a) 750 Semi-angle (b) 600 Semi-angle (c) 450 Semi-angle

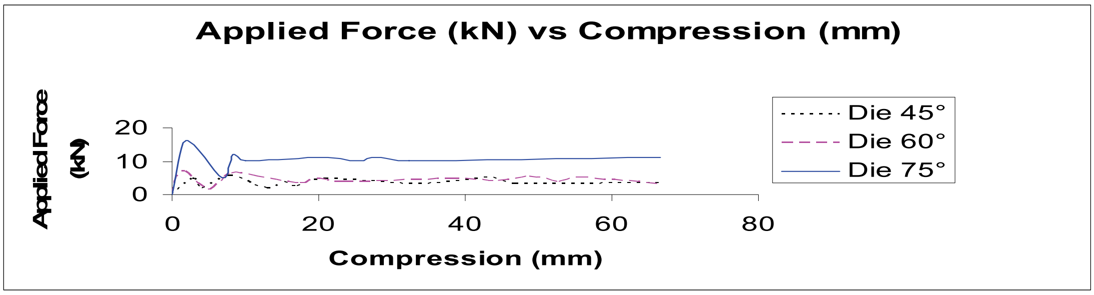


Figure 4: Applied Force-compression Curves for 4 Initial Slits with Various Semi Angle Die

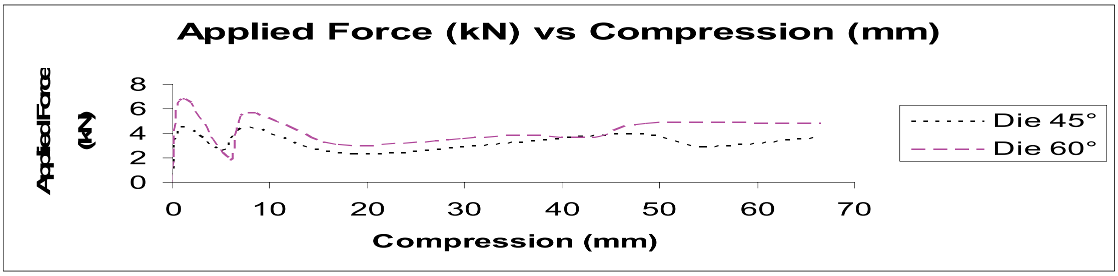


Figure 5: Applied Force-compression Curves for 6 Initial Slits with Various Semi Angle Die

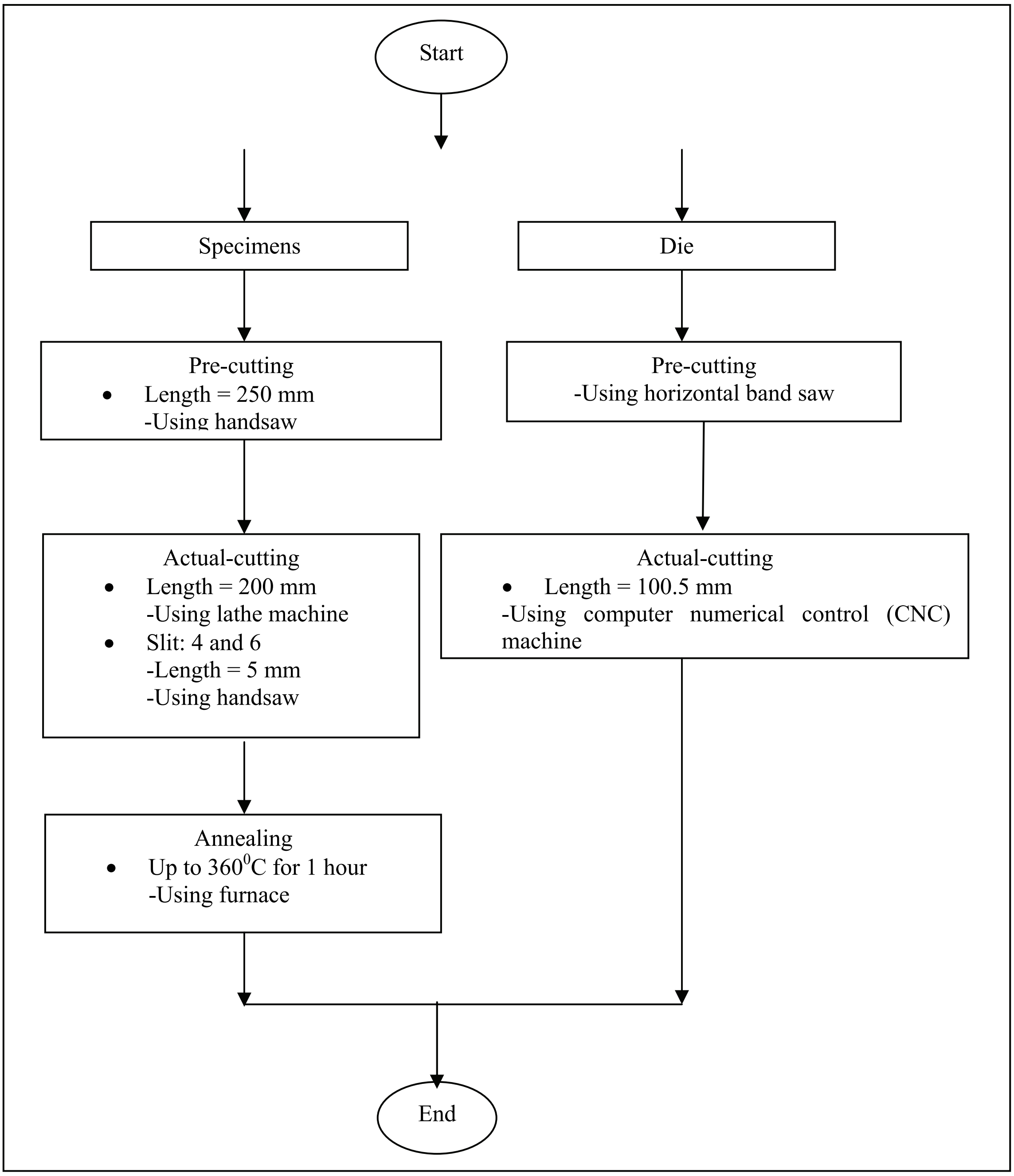


Figure 3: Flowchart of Tube and Die Preparation for Tube Splitting

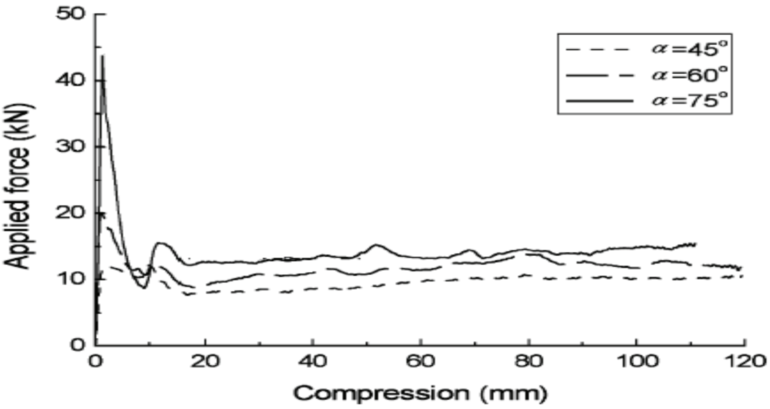


Figure 6: Applied force-compression Curves for Mild Steel Tubes (Huang et al, 2002)

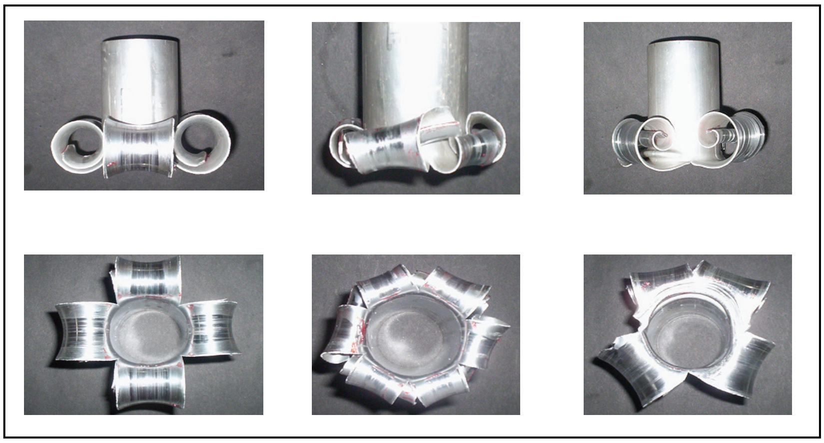


Figure 7: Deformation Mode for Tube Splitting with Initial 4 Slit

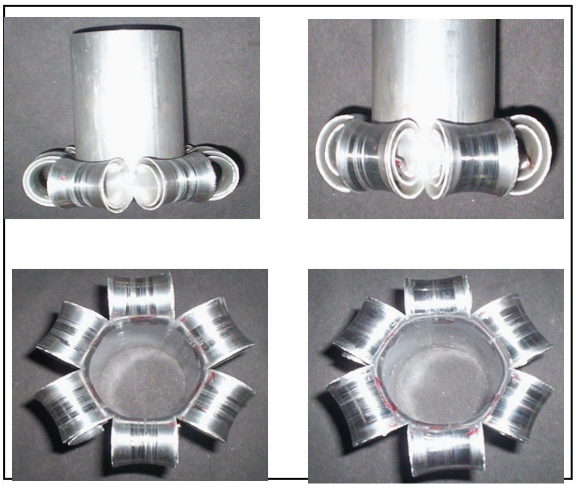
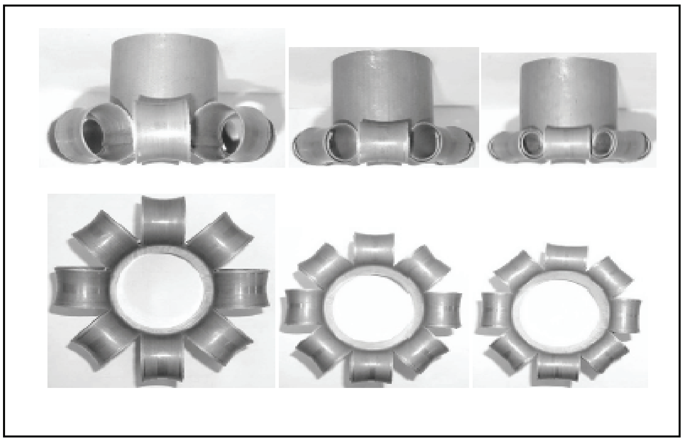


Figure 8: Deformation Mode for Tube Splitting with Initial 6 Slit



(a) (b) (c)

Figure 9: Mild Steel Tubes after Compressed Onto: (a) 45° (b) 60° (c) 75° Semi Angle Die (Huang et al, 2002)

TABLES

Table 1: Peak Load and Mean Load for Respective Slit and Semi Angle Die

Initial Saw Cuts	Semi Angle α (0)	Peak Load (kN)
4	45	4.6
	60	6.9
	75	16.1
6	45	4.5
	60	6.7

Table 2: Number of Splits Before and After Test

Semi-angle die	Number of split		Remarks
	Before test	After test	
45	4	4	Number of slits remained
60		6	Number of slits branched
75		4	Number of slits remained with slight tearing and merging
45	6	6	Number of slits remained
60		6	Number of slits remained