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A Study of Shear Stress Intensity Factor of PP and HDPE by a Modified Experimental Method together with FEM

Md. Shafiqul Islam, Abdullah Khan, Sharon Kao-Walter, Li Jian

***Abstract*—**Shear testing is one of the most complex testing areas where available methods and specimen geometries are different from each other. Therefore, a modified shear test specimen (MSTS) combining the simple uniaxial test with a zone of interest (ZOI) is tested which gives almost the pure shear. In this study, material parameters of polypropylene (PP) and high density polyethylene (HDPE) are first measured by tensile tests with a dogbone shaped specimen. These parameters are then used as an input for the finite element analysis. Secondly, a specially designed specimen (MSTS) is used to perform the shear stress tests in a tensile testing machine to get the results in terms of forces and extension, crack initiation etc. Scanning Electron Microscopy (SEM) is also performed on the shear fracture surface to find material behavior. These experiments are then simulated by finite element method and compared with the experimental results in order to confirm the simulation model. Shear stress state is inspected to find the usability of the proposed shear specimen. Finally, a geometry correction factor can be established for these two materials in this specific loading and geometry with notch using Linear Elastic Fracture Mechanics (LEFM). By these results, strain energy of shear failure and stress intensity factor (SIF) of shear of these two polymers are discussed in the special application of the screw cap opening of the medical or food packages with a temper evidence safety solution.

***Keywords*—**Shear test specimen, Stress intensity factor, Finite Element simulation, Scanning electron microscopy, Screw cap opening.

I. INTRODUCTION

IN medical or food packaging, blister and bottle screw cap are widely used types of the packaging where opening of the package joints requires shear loading. Fig. 1 shows an example of a medical package with jointed screw cap. Two of the most used polymers in this field are Polypropylene (PP) and High-density polyethylene (HDPE). Both polymers are petroleum based thermoplastic. Investigation of shear fracture properties of these and similar polymers are useful for efficient and user-friendly design of package opening and temper evidence safety solution. Traditionally Iosipescu and V Notched Rail tests are done to measure shear modulus, shear strength, poisson's ratio and fracture properties. In Iosipescu, a notched specimen (Fig. 2 (a)) is loaded asymmetrically at four co-planer points to bend it and pure shear state is achieved along the imaginary narrow strip joining the notches [1].

Fig. 1 Screw cap sealed medical package that needs shear failure for opening

Arun Krishnan and L. Roy Xu [2] show a similar loading and proposed formula for calculating shear stress intensity factor

$$K_{II} = \frac{P}{W}\sqrt{\pi a}F_{II}\left(\frac{a}{W}\right) \quad (1)$$

Here, 'P' is the applied load, 'W' is width, 'a' is crack length, 't' is the thickness of the short-beam shear specimen and 'F' is a dimensionless parameter.

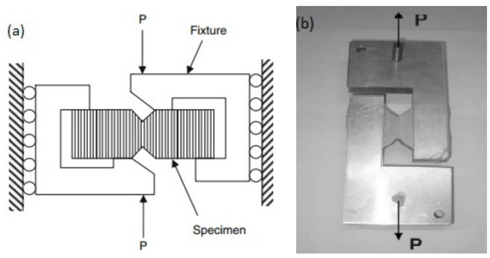

Fig. 2 Experimental setup of (a) Iosipescu shear test and (b) V-Notched rail shear test

In the case of V-Notched Rail test, the notched specimen is attached to a rail as in Fig. 2 (b) and loaded in uniaxial tension. The geometry is a hybrid where the test specimen and the rail of a V-Notched Rail Test join together with minor modification to give the new shape. The advantage of V-

Md. Shafiqul Islam is with the Dept. of Mech. Eng., School of Eng., Blekinge Institute of Technology, SE 37179, Karlskrona, Blekinge, Sweden (phone: 0046739750480; e-mail: shafiq099@ gmail.com).

Abdullah Khan was with the Dept. of Mech. Eng., School of Eng., Blekinge Institute of Technology, SE 37179, Karlskrona, Blekinge, Sweden (phone: 00923018427373; e-mail: abdullahgiki@gmail.com).

Sharon Kao-Walter is with the Dept. of Mech. Eng., School of Eng., Blekinge Institute of Technology, SE 37179, Karlskrona, Blekinge, Sweden and Faculty of Mech. & Elec. Eng., Shanghai Second Polytechnic University, Shanghai, China (phone: 0046455385506; e-mail: sharon.kao-walter@bth.se).

Li Jian is with Faculty of Mech. & Elec. Eng., Shanghai Second Polytechnic University Shanghai, China (phone: 0046727832306; e-mail: lijian2008d@sina.com).

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Notched Rail test over the Iosipescu is that, it can be used for larger deformation of test specimens. But both tests require the user to be very careful to setup equipments and attach fixtures with the test specimens. This paper investigates usability of a modified shear test specimen (see Figs. 3 (b) and 4 (a)) with no attachments and suggesting a simpler shear test method. Similar shape of shear specimen was proposed by Leslie Banks-Sills and M. Arcan [3] and modified by many authors including F. Gao et al. [4] The modified specimen in this work looks like a V-notched rail test setup, the fixture being a part of the specimen.

To find whether the ZOI in specimen undergoes shear loading, sate of stress is required to be checked during uniaxial tensile loading. There are several ways to check the sate of loading of a specimen. By definition states stress triaxiality $\sigma_m/\sigma_v = 0.33$ for uniaxial tensile loading and $\sigma_m/\sigma_v = 0$ for pure shear loading [5]. A quantitative comparison between normal (σ_{11}) and shear stress (σ_{12}) in the zone of interest can also conclude about the state of loading. [6]. When σ_{12}/σ_{11} is larger than one, shear loading is larger and as this value increases, shear loading becomes more dominant.

For calculation of shear failure the quantity stress intensity factor, K_{II} helps to predict the stress state near crack/notch tip. Linear elastic fracture mechanics (LEFM) predicts equation,

$$K_{II} = \tau_{xy}(\sqrt{\pi a})gII \quad (2)$$

g_{II} being the shear geometry correction factor for MSTS.

II. Physical Experiments

Materials used for the experiments are prepared in material testing laboratory of a packaging company. Shaping technique used for making PP and HDPE plates is injection molding from several points to achieve better isotropic properties. The dogbone tensile and modified shear test specimens as described above are then cut for the material plates by using water jet. Notches in shear specimen are cut by hand using sharp blades.

All tests are performed on MTS Qtest 100 Tensile testing machine with a load cell of 2 kN at room temperature. High data acquisition rate and slow test speed is used to get more accurate data. Tensile and proposed modified shear test specimens for both HDPE and PP are referred as Sp1 and Sp2 respectively are as in Fig. 3.

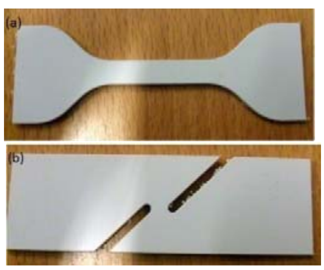

Fig. 3 (a) Tensile dogbone specimen and (b) proposed shear specimen (without notch)

Two ends of the specimen are fixed to hydraulic grip orienting vertically and then upper grip is elevated to induce tension. Co-relation between tensile force and displacement provides young's modulus, poisons ratio, plasticity data.

The geometry of the dog bone specimen used in tensile test has an effective length of 22.72mm, width of 6mm and thickness of 0.69mm according to ASTM E8 standard for flat test specimen. The shear specimen can be divided into two parts as a loading frame (Fig. 4 (a)) and effective test specimen (Fig. 4 (b)) that can be imagined as cross section containing the notches [4].

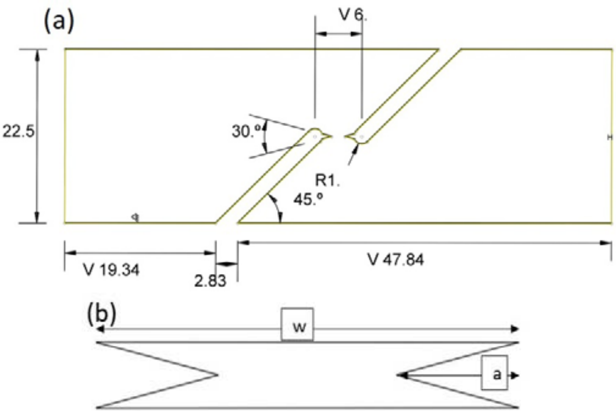

Fig. 4 (a) Loading frame (b) Effective test specimen

Thickness of the specimen is 0.69 mm and notches are with an angle of 30 degree. Notch depth *'a'* is arbitrary.

A. Uniaxial Tensile Test

PP and HDPE are loaded in uniaxial tension to find the correlation data points between force and extension. Test speed is 10mm/min with data acquisition rate of 10 Hz.

Fig. 5 Tensile testing of PP

From these data points true stress and strain curve is plotted which provided information about the Young's modulus, plastic stress, plastic strain, strain rate etc that later used in the numerical material model. Standard poisson's ratio of 0.45 for PP and 0.42 for HDPE are used for later calculation.

B. Shear Test

The geometry of the specimen is finalized after initial finite element calculation and trial and error of many FEM simulations. The specimen is uniaxially loaded to find force-elongation correlation. For strain calculation, cross section joining the notch tips is considered. This provided shear stress strain relation of the materials.

C. SEM study of Shear Fractured Surface

The shear fractured surface between the notches of PP and HDPE are coated with gold and observed under scanning electron microscope.

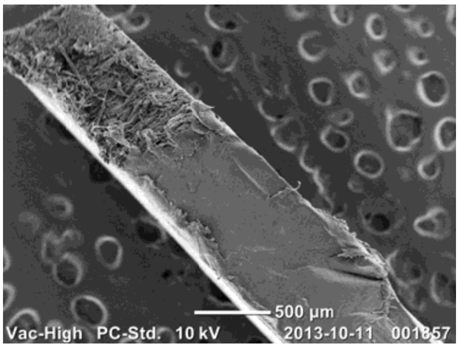

Fig. 6 SEM of PP fracture surface

The fracture surface includes a mirror like polished region. However, in shear loading there is also a rough and transition area near the initial crack front, as shown in Fig. 6. The presence of higher stresses in shear loading can be one reason for transition areas in shear fracture surfaces, because at some stages of crack growth, the stress becomes high enough to initiate secondary local cracks that give rise to the rough area. Another reason for higher roughness of surfaces is the fact that, in shear loading, fracture does not take place along the initial pre-crack. In addition, once fracture initiates, it usually does not grow in straight line and the crack path is formed. The formed path of crack growth can be due to the maximum tangential stress direction changes as the crack propagates. Thus, at each step of crack propagation, the crack grows in a new direction which has the maximum tangential stress. The crack can also be another reason for the transition and rough fracture surfaces in the specimens fractured under shear loading.

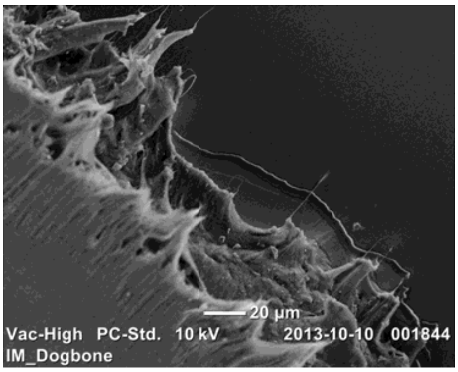

Fig. 7 SEM of HDPE fracture surface

Accompanying the shear fracture, fibrils of HDPE and the extension of HDPE appear which suggests a brittle behavior. For parallel sample, many thin and long strips are parallel to each other and are homogeneously distributed (Fig. 7) when the crack propagation direction is perpendicular to the shear flow. The result indicates the development of crack is a continuous process by which a lot of energy is dissipated.

III. Finite Element Method

After creating the specimen in the commercial finite element program Abaqus 6.11 [7], two different material models are used for simulation. In first case, constitutive plasticity and damage model of the material is generated from the experimental data and used to inspect stress states in σ_{11} (Normal) and σ_{12} (Shear) directions of the MSTS and Iosipescu test. In second case, for finding shear stress intensity factor (SIF), linear elastic isotropic material model is used in calculation. In both cases, applied stress state is 3D and building elements are C3D8R: 8-node linear brick of optimized size varying in different region of the geometry. Customized mesh distribution has been used where most dense mesh can be found around fracture zone (ZOI). An optimization of mesh in terms of convergence of simulation result (Force vs. Displacement) is done to find convenient mesh size, which is 120 microns (smallest). Shear stress intensity factor is usually used in linear elastic fracture mechanics to characterize the local crack-tip/crack-line stress and displacement fields. They are related to the energy release rate (the J-integral) through direction of crack initiation and can be evaluated using maximum energy release rate criterion which postulates that a crack starts to propagate in the direction which maximizes the energy release rate [7]. Crack type used to define notch is contour integral.

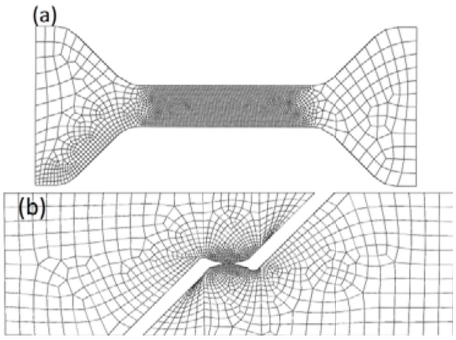

Fig. 8 Mash of tensile and shear specimen

Boundary conditions are applied to restrict all freedom of movement at one end of the model and the other end is coupled to a reference point, which is further given a displacement outwards; causing elongation. For Iosipescu test simulation, the boundary conditions are as in Fig. 2 (a). Set of units used inside Abaqus is length-mm, time- ms, mass-g, force-N.

IV. Result and Discussion

Numerical and experimental results of force and elongation of PP and HDPE dogbone tensile specimen are as in Fig. 9. The results are in good agreement which allows us to use the numerical material model to compute stress distributions and stress intensity factor.

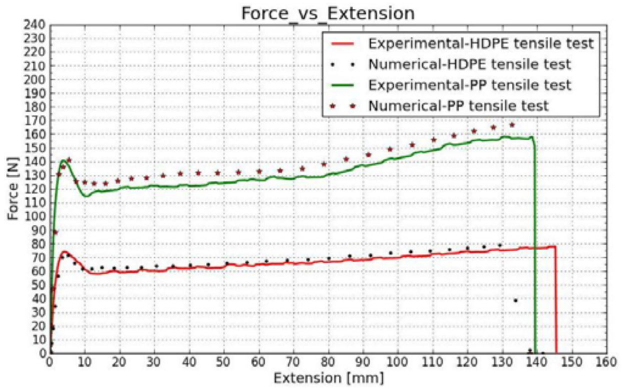

Fig. 9 Comparison of experimental and numerical tensile results of PP and HDPE dogbone specimen

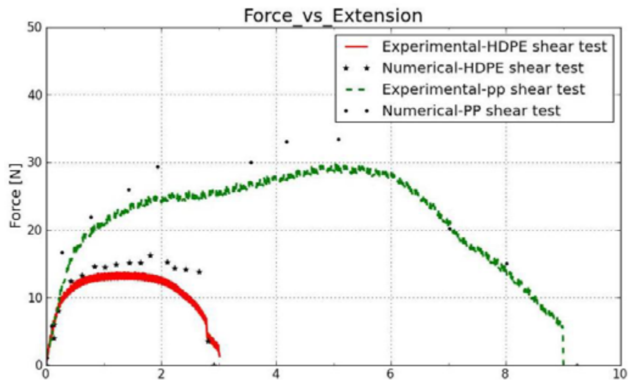

Fig. 10 Co-relation between force and elongation of HDPE and PP (Numerical results plotted in dot)

Numerical and experimental co-relations between force and elongation of the shear specimen are as in Fig. 10.

A. Observation of Stress Distribution

Stress state is numerically investigated on the σ_{12} and σ_{11} around the notches for 50% strain level. Maximum shear stress, σ_{12} has the magnitude of 13 MPa across the cross-section of ZOI, where as the maximum normal stress, σ_{11} is around 1.5 MPa, which is nine times lower to indicate shear stress domination. This can be seen in the color coded contour for σ_{11} and σ_{12} of the specimen in Fig. 11. The distribution shows domination of σ_{12} over σ_{11}. A quantitative relation between ln (σ_{12}/ σ_{11}) and shear strain (%) is in Fig. 12. In this case, stress values are computed from numerical simulation at the centre node of the ZOI. This also satisfies domination of shear stress. For a further comparison of stress distribution in MSTS, a numerical simulation of frequently used Iosipescu shear test is computed in Abaqus. The part experiencing shear load in the Iosipescu specimen is kept of the same dimension as in MSTS and equal level of strain is applied. 3D contour stress distribution of σ_{12} and σ_{11} for this simulation are shown in Fig. 13. A close resemblance between the results justifies the effectiveness of modified specimen for shear testing.

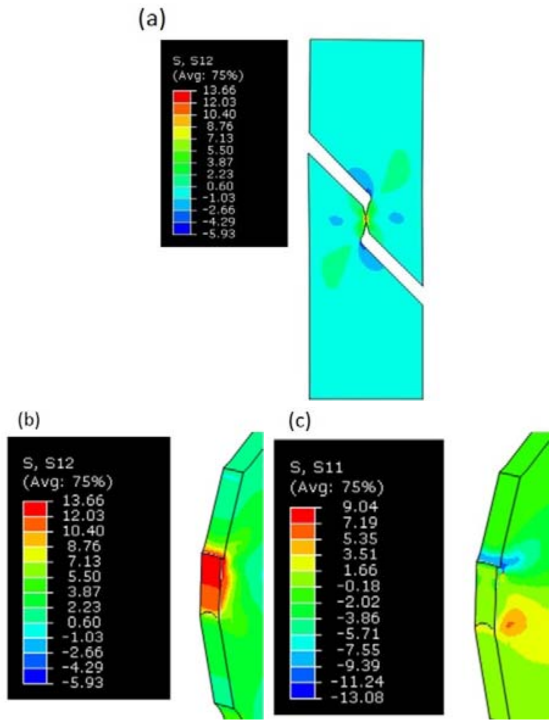

Fig. 11 3D contour of stress distribution during modified specimen loading (a) Shear stress (b) Zoomed shear stress (c) Normal stress

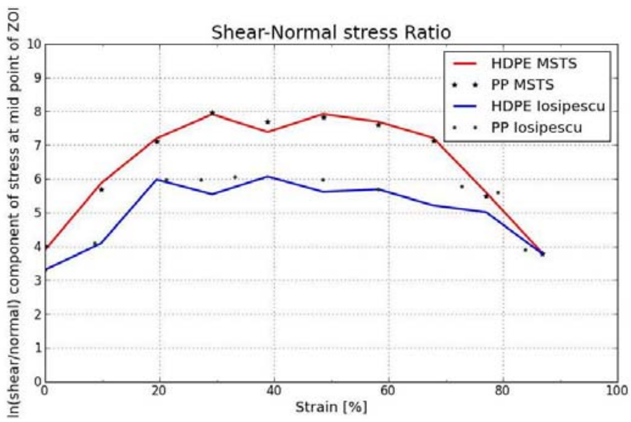

Fig. 12 Strain (%) vs ln(σ_{12}/ σ_{11}) for MSTS and Iosipescu

σ_{12} has the magnitude of 14.04 MPa across the cross-section of ZOI, where as σ_{11} is around 1.66 MPa. This is not clearly conclusive but in most cases MSTS shows higher level of shear stress domination.

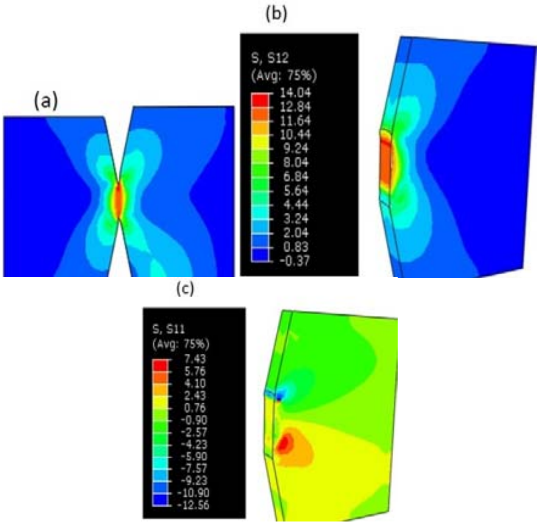

Fig. 13 3D contour of stress distribution during Iosipescu specimen loading (a) Shear stress (b) Zoomed shear stress (c) Normal stress

B. Geometry Correction Factor

Stress intensity factor is numerically evaluated and using (2), geometry correction factor 'g_{II}' is calculated for different notch length 'a' of 30 degree notch angle and fixed 'w' (See Fig. 4 for 'a' and 'w') as in the Table I. K_{II} (Shear stress intensity factor) is linearly proportional to shear stress τ_{xy}, so, values at arbitrary state of loading are selected for calculation.

TABLE I
GEOMETRY CORRECTION DATA

a/w	K_{II} HDPE	K_{II} PP	T_{xy} HDPE	T_{xy} PP	g_{II} HDPE	g_{II} PP
0.0955	3.78	5.44	7.31	10.23	0.41	0.42
0.1235	5.04	7.12	8.24	10.83	0.42	0.45
0.1573	8.53	11.65	7.54	9.39	0.68	0.76
0.1966	10.32	9.03	10.6	15.12	0.43	0.32
0.2359	7.82	9.72	14.06	15.81	0.23	0.3
0.2771	6.46	11.6	10.37	15.19	0.34	0.35
0.2996	6.8	14.7	11.39	15.53	0.3	0.42
0.3183	8.03	13.78	11.28	17.78	0.33	0.33
0.3389	9.63	15.11	10.64	16.24	0.39	0.39

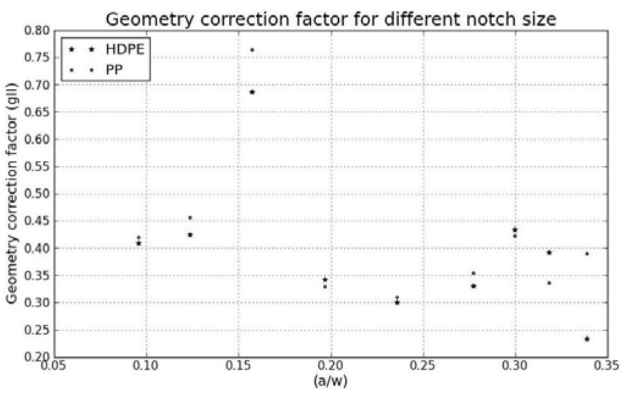

Fig. 14 Relation between (a/w) and geometry correction factor of MSTS

Using the least squared root fitting method the results can be co-related with a sum of sine function as in (3).

$$g_{II}\left(\frac{a}{w}\right) = 1.291\sin\left(1.033\left(\frac{a}{w}\right) + 2.607\right) + 0.1429\sin\left(45.53\left(\frac{a}{w}\right) - 5.742\right) + 0.06811\sin\left(75.49\left(\frac{a}{w}\right) + 2.27\right) \quad (3)$$

Shear stress intensity factor range for HDPE is 3.78-10.32 and for PP is 5.44-15.11.

V. CONCLUSION

The aim of the work is to modify a shear specimen that can be used for shear testing in simple tensile testing machine without any complicated attachment. Two different polymers are tested and simulated to find shear stress domination during tensile loading. From the stress distribution of σ_{11} and σ_{12} the MSTS specimen geometry justifies its use for shear testing. The comparison of different components of stress tensor of modified specimen with standard Iosipescu shear test stress distribution at same strain level shows the advantage of MSTS to find shear properties. Shear test results in Fig. 10 shows the strain energy (area under curve) for PP and HDPE shear failure. A calculation of strain energy by integration of curve equation obtained by fitting test data, shows that the value for PP is eight times higher than HDPE. But the ultimate shear strength is just two times higher. It happens as PP undergoes larger shear deformation before failure. This makes HDPE a more favorable material for packages those experience shear failure for opening. Shear fracture studies of discussed materials are necessary for other different designs of screw cap joints. The SEM study shows PP and HDPE fracture is partially brittle so established geometry correction factor for LEFM study can be used to find shear stress intensity factor. Finally, K_{II} range for HDPE is 3.78-10.32 and for PP is 5.44-15.11. Energy release rate is proportional to the stress intensity factor squared and expresses the required energy to create new fracture surface. So, PP screw cap is much harder to break and separate the joints.

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