An Analysis of Rotationally Moulded Sandwich Structure's Repeated Impact Properties

Abu Saifullah[1, 2, a)], Ben Thomas[2], Robert Cripps[3], Kamran Tabeshfar[2], Lei Wang[4]

[1]Advanced Polymers and Composites (APC) Research Group, School of Mechanical and Design Engineering, University of Portsmouth, Portsmouth, PO1 3DJ, UK.
[2] School of Design and Engineering, Talbot Campus, Bournemouth University, Bournemouth, BH12 5BB, UK
[3]Longitude Consulting Engineers Ltd., Southampton, SO15 2EU, UK
[4]Matrix Polymers, Northampton, NN3 9AG, UK

[a)] Corresponding author: abu.saifullah@port.ac.uk

Abstract. Repeated impact properties of fully recyclable rotationally moulded polyethylene (PE) sandwich samples were experimentally investigated in this work. Testing was carried out with an impact force sensor attached drop weight impactor at 20 J to 50 J energy levels. These sandwich structures used in marine, automotive, large tanks and other applications, are susceptible to small damage due to impact events with floating debris, collisions or friction with other vehicles, crafts etc. in their service life which can grow with time and repeated impacts leading to a catastrophic failure. To avoid this unexpected situation, an in-depth understanding of repeated impact properties of this sandwich structure is essential. The repeated impact properties were analysed in terms of impact force-deflection, maximum impact force, impact damage and the total number of repeated impacts needed for sample penetration. A lower impact energy level showed a higher total repeated impact events to penetrate sandwich samples fully. The maximum impact force vs the repeated impact number figure exhibited three different regions which are related to the damage mechanisms of tested rotationally moulded sandwich samples.

Keywords: Rotational moulding, skin-foam-skin, repeated impact, damage, polyethylene (PE).

INTRODUCTION

Rotational moulding is a unique, growing and inexpensive plastic manufacturing process especially for large hollow products [1-4] . In this process, sandwich structures can be produced having two skins and a foam core which offer high bending stiffness, light weight, thermal and acoustic insulation and high interfacial strength of skin and foam core layers [5]. In addition, these sandwich structures are fully recyclable as same thermoplastic skin and foamed core materials such as PE are used. For the manufacturing of rotationally moulded sandwich structure, a layer by layer sequential procedure [6] is used in both the conventional and the new drop-box manufacturing processes [7]. These composite structures used in canoes, kayaks, boat hulls and automotive applications such as car bumpers etc. can get many small impacts and surface damage created at various stages of their lifespan such as repeated impacts due to the collision, touching, rubbing and friction with other crafts, docks, grounding, tool dropping during manufacturing etc. [8, 9]. This damage is typically very small and can't be detected by the naked eye. It is possible that the damage incurred in an initial impact can grow with time and repeated impacts and cause a catastrophic failure. To address this, there is a need for a greater understanding of the effects of accumulated damage to the sandwich structure from repeated impacts to better predict the materials behaviour in above mentioned applications.

Investigation of the impact response (single impact event) of rotationally moulded sandwich structures has been reported in the published literature recently [1, 5, 8]. Research work on low velocity repeated impact properties has not been investigated until now and therefore, little academic literature is found. However, there have been some research publications in the related field of repeated impact properties of fibre reinforced composites, including sandwich structures comprised of glass fibre and carbon fibre composites [10], glass, carbon and Kevlar composites, short glass fibre reinforced polycarbonate, graphite/epoxy composite plates, glass-epoxy composites, thermoplastic matrix composites [9], foams [11] and honeycomb core sandwich panels. In most of the experimental investigations an instrumented drop weight impact testing machine was used for testing repeated impact properties and generally the sandwich panels were tested under multiple impact shocks at the same energy level or at various energy levels until penetration of the sample had been occurred. Abdullah Akatay et al. [12] studied repeated impacts of honeycomb sandwich panels and observed a significant lower compression property for the repeated impacted samples. Therefore, it was concluded that the total number of impact events to penetrate the sandwich samples was increased with lower energy levels. The same observation was collaborated by other researchers. A relationship between the impact event numbers and the energy level was studied which was useful to predict the impact-fatigue life of a sandwich composite [13] and was found that up-to a certain energy level the curve shows parabolic variation. Lower than this certain impact energy value, the impact number up-to the penetration increased suddenly.

In this work, an experimental investigation was carried out on repeated impact properties of sandwich structures manufactured of rotationally moulding process using low velocity repeated impact condition to get an understanding of sandwich structure behaviour during repeated impact events in marine and automotive applications. For low velocity impact, less than 10 m/s was suggested, whereas, Abrate [14] mentioned a low velocity impact event up-to 100 m/s. In addition to impact velocity, (m) the impactor mass to the sample mass ratio (m >8) is also crucial for the low velocity impact test condition. PE sandwich structure samples were manufactured and repeated impact tests were conducted at 20, 30, 40 and 50 J impact energy levels with a drop weight impact tester. Tests were conducted under multiple impact shocks at all energy levels until the tested sample showed full penetration. Comparisons were made between the results of single and repeated low velocity impact shocks, particularly in terms of maximum impact force, deflection of the sandwich panels and impact event numbers. Damage was investigated at impacted top and bottom surfaces to develop an understanding of the effect of repeated impact events on the sandwich structure.

EXPERIMENTAL

Rotational Moulding of Sandwich Structure

A commercially available roto-mould grade Polyethylene (PE) was used for the manufacture of sandwich samples in both skin and foam layers as it offers an excellent rotational mould ability and better fracture properties, while, for the manufacture of foam core layer, a blowing agent blended PE was used. MFI, density, yield stress of PE for skin (trade name Revolve M-601) and foam core (trade name M-56) layers are 3.50 g/10 mins, 0.949 g/cm^3, 21.5 MPa and 3 g/10 mins, 0.310g/cm^3 respectively. Material details were supplied by the material supplier (Matrix Polymers, UK). Yield stress of PE for foam layer was not found from material supplier. The Ferry Roto-speed Carousel type rotational moulding machine with a 300 mm cube mould was used to manufacture samples at Matrix Polymers Ltd. UK facilities, with a total 8 mm thickness (2 mm top and bottom skin thickness, 4 mm foam core layer thickness) since this thickness combination is mostly used in automotive and marine leisure craft applications and also easy to mould in the rotational moulding process. The amount of polymer powder used to manufacture each layer of this sandwich structure was 850 g, 300 g and 800 g for the top skin, foam core and bottom skin layers respectively.

Repeated Impact Test and Damage

Samples of 110 mm × 110 mm dimension were cut from moulded sandwich structure panels, clamped and repeatedly impacted with a 12 mm diameter hemispherical indenter using a drop weight impact tester at 20, 30, 40 and 50 J impact energy levels. From an initial study, it was observed that the manufactured sandwich structures (2+4+2 mm, top skin + foam +bottom skin) got penetrated at 80 J and significant scratches in the bottom skin at 70 J energy levels. Therefore, the energy levels for the repeated impact test were kept between 20 J to lower than 70 J. The impact energies were chosen at 20 J, 30 J, 40 J and 50 J and these energy levels maintained low velocity impact test conditions [14]. The samples were subjected to impacts repeatedly up-to penetration at each energy level. The impactor weight was 9.1 kg. Three samples were tested here at each energy levels. A 22.4 kN piezoelectric impact force load sensor attached to the hemispherical indenter. The impact force, deflection and total number of impact events data generated in repeated impact tests were acquired through an oscilloscope (Picoscope IEPE 4242). The frictional effect between the impactor and the test samples was not considered here. Great care was taken during the test so that every repeated impact event occurred at the same location on the samples. Here, force-deflection curves only showed the primary impact at each impact events. In the repeated impact test, there was no anti-rebound system available and development of this would be a useful addition for the future works. Damage at the top and bottom skin following repeated impact events was identified and analysed with a digital optical microscope.

RESULTS AND DISCUSSION

Repeated Impact Properties

Force-deflection curves obtained in the repeated impact testing are presented here in Figure-1 (A-D) for 20,30, 40 and 50 J respectively. The number of repeated impacts before the penetration of samples was found higher for the lowest energy level at 20 J. This was observed to decrease with increasing impact energy levels as expected. The sandwich samples were found to be penetrated after 273rd repeated impacts at 20 J (Figure-1-A). Four impacts were found to penetrate the sample at 50 J (Figure-1-D). For 30 and 40 J energy levels, it was counted as 48th (Figure 1-B) and 11th (Figure-1-C) repeated impacts respectively.

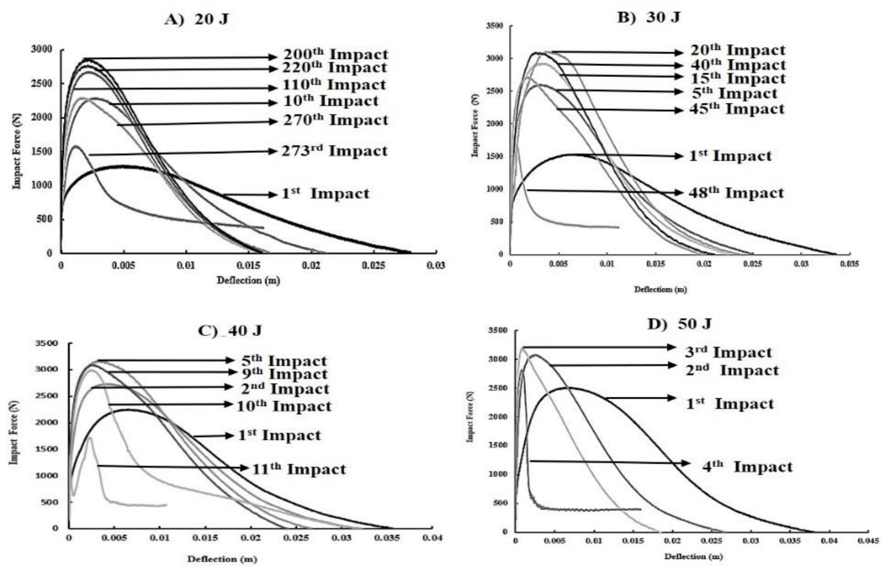

FIGURE 1. Impact force-deflection curves of repeated impact tests at A) 20 J, B) 30 J, C) 40 J and D) 50 J energy levels.

At the 273rd, 48th, 11th and 4th impact force-deflection curves of the 20, 30, 40 and 50 J energy level tests respectively, the unloading portions were found not to touch the X-axis unlike other impact events shown in Fig.1-(A-D) because of impactor penetration through the tested sandwich samples. After the first impact at each energy level, deflection values decreased with increasing number of impacts. At 20 J energy level, deflection reduced from 28 mm to 5 mm whereas at 50 J it reduced from 40 mm to 5 mm due to the reduction of impact resistance of tested samples with increasing number of impacts. It can be seen that as a general trend, Fmax (maximum impact force) was noticed to rise quickly with increasing number of impacts up to a certain number of repeated impact events for all energy levels. After that they reduced until the samples became penetrated. At 20 J, the maximum impact force was identified as 1250 N in the first impact, it was increased to 2856 N in the 200th impact and then reduced to 1500 N in the 273rd impact where the sample failed. Similar observations were also noticed at 30 J, 40 J and 50 J energy level.

The changes in maximum impact force (Fmax) are illustrated in Fig. 2 (A-D) for repeated impact tests. Three regions were identified in the Fmax curves. In the first region, Fmax values increased sharply due to the permanent compressive deformation behaviour and densification of the foamed core layer of the sandwich sample. The maximum impact force levelled off after a limited number of impacts to form a plateau region. In this region, increasing consolidation and thickness reduction of the foamed core layer, and the crack start and propagation in the bottom layer were observed. The Fmax was found to reduce at the end of this region as the bottom surface was seen to lose its load carrying capacity and the foamed core layer also showed the highest thickness reduction. As a result, in the third region the impact energy absorption capacity was dropped and the impact dart started to penetrate the top surface and ultimately the whole sample. The simalr observation for Fmax values changes in repeated impact test was also reported in other studies [11].

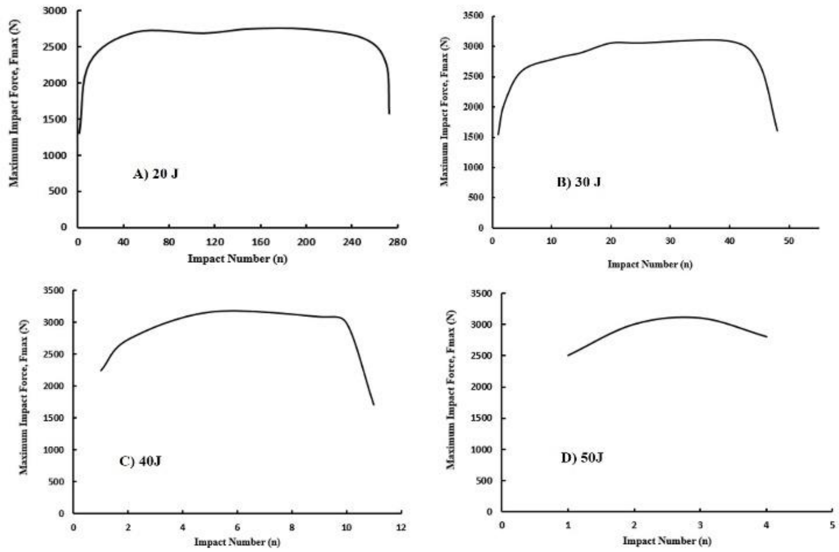

FIGURE 2. Changes of Fmax values during the repeated impact tests at A) 20 J, B) 30 J, C) 40 J and D) 50 J energy levels.

Damage Occurred in Repeated Impact Test

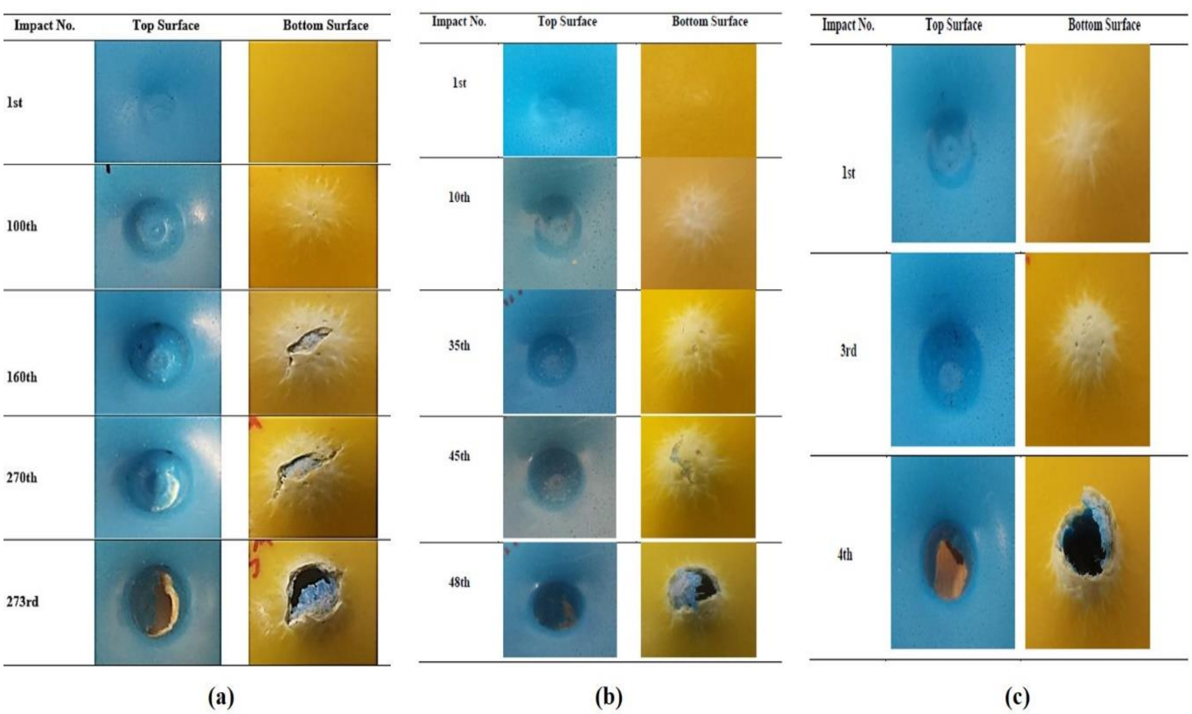

FIGURE 3. Top and bottom surface damage during repeated impact test of sandwich structures at (a) 20 J; (b) 30 J and (c) 50 J impact energy levels.

Figure 3 (a, b, c) show images of top and bottom surface damage of repeated impacted samples at 20 J, 30 J and 50 J energy levels. With 20 J (Fig.3(a)), in the first impact only a small amount of indentation depth on the top surface was clearly observed without any deformation visible in the bottom surface. The indentation depth in the top surface was increased for the increase in impact numbers. Therefore, crushing and consolidation of the core layer with corresponding overall local thickness reduction of the sandwich section was observed. Deformation in the bottom surface was also noticed to increase with impact number once crushing of the core layer had taken place.

By the 100th impact, these damage modes were clearly seen on the samples due to the plastic and ductile deformation scratches (visible as white marks on the sample) were found in the bottom surface; in the core layer thickness reduction was observed and in the top surface, an increase in indentation depth was occurred. With a further increase in impact numbers, scratches in the bottom surface were found to grow continuously and started to create cracks or fractures in the bottom surface. After the initial cracks appeared in the bottom surface, they increased slowly with impact number, at this stage most of the impact load was carried by the top surface layer. In the impact zone, with the growing top surface indentation depth, the core layer also got compressed and cracked leading to the initiation of top surface cracks, and the final penetration of the whole structure. Images at the 160th, 270th and 273rd impact of top and bottom surfaces (Fig. 3(a)) reveal these features. A similar mechanism for damage initiation and propagation was also observed at 30 J (Fig. 3(b)) and 50 J (Fig. 3(c)) and for other energy level (40 J), tested in this work.

CONCLUSION

In this study, it was clearly found that the number of repeated impacts for the penetration of tested samples is the maximum for lower impact energy levels. At 20, 30, 40 and 50 J repeated impact test, total number of impact events recorded to penetrate the sample was 273, 48, 11 and 4 respectively. In the maximum impact force vs. impact number curves, three regions were identified which relate to the damage mechanisms of the structure. Indentation depth in the first impact event was found to increase with impact numbers; created core crushing and consolidation in the core layer with plastic deformation and scratches in the bottom surfaces. For further increasing impact numbers, cracks were seen to develop in the bottom surfaces, cracking in the core layer leading to crack initiation and propagation in the top surfaces and finally full penetration of the sandwich samples.

Guidelines for rotational moulding product industries -The repeated impact resistance was shown to decrease significantly as the sample deformation capacity per impact decreases with the increasing impact numbers, implying that the real-world impact resistance of these sandwich structures can be severely compromised after just a limited number of impacts in the same location especially at higher energy levels, for instance at 50 J. The implications of these results for designers are that particular focus must be given to regions of rotationally moulded sandwich structure products used for various applications- marine and automotive sectors etc., where repeated impact is likely to occur in real life scenarios.

ACKNOWLEDGEMENT

Matrix Polymers, Northampton, UK helped in this work through their rotational moulding facilities for manufacturing of sandwich samples. Longitude Consulting Engineers Ltd. supported this study by providing their experiences in rotationally moulded product developments.

REFERENCES

1. C. Casavola, V. Moramarco and C Pappalettere, Fatigue & Fracture of Engineering Materials & Structures **37**, 1377-1385 (2014).
2. R.C. Vázquez-Fletes, L.C. Rosales-Rivera, F.J. Moscoso-Sánchez, et al., Polymer Engineering & Science **56**, 278-286 (2016).
3. F.E. Hanana, D.Y. Chimeni, D. Rodrigue, Polymers and Polymer Composites **26**, 299-308 (2018).
4. A. Saifullah, B. Thomas, K. Tabeshfar and R. Cripps, R. 2016, "Impact properties analysis of rotationally molded polyethylene and polypropylene for a wide range of temperatures", in Annual Technical Conference – ANTEC-2016, Conference Proceedings, pp. 1686-1689.
5. A. Saifullah, B. Thomas, R. Cripps, K. Tabeshfar and L. Wang, Polymer Engineering & Science **60**, 387-397 (2020).
6. E. Archer, E. Harkin-Jones, M.P. Kearns and A.M. Fatnes, Journal of Cellular Plastics **43**, 491-504 (2007).
7. K. Duffy, U.S. Patent No. 4,952,350 (28 August 1990).

8. A Saifullah, L. Wang, A. Barouni, et al., Journal of Materials Research and Technology **15**, 3915-3927 (2021).
9. O. Çoban, M.Ö. Bora, T. Sinmazçelik, İ. Cürgül and V. Günay, Materials & Design **30**, 628-634 (2009).
10. T. Sinmazçelik, A.A. Arıcı and V. Günay, Journal of Material Science **41**, 6237-6244 (2006).
11. C. Atas and C. Sevim, Composite Structures **93**, 40-48 (2010).
12. A. Akatay, M. Ö. Bora, O. Çoban, S. Fidan, and V. Tuna, Composite Structures **125**, 425-433 (2015).
13. M.Ö. Bora, O. Çoban, T. Sinmazçelik, İ. Cürgül and V. Günay, Materials & Design **30**, 145-153 (2009).
14. S. Abrate, Applied Mechanics Reviewes **50**, 69-82 (1997).