Influence of fall height setting on drop weight tested polypropylene and its crack growing

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Abstract: - This study deals with polypropylene (PP) which was subjected the drop-weight test. PP is a semi-crystalline thermoplastic polymer which is commonly used in many indoor applications and also in the automotive industry in the car interiors. Injection moulded PP samples were subjected the penetration test at different fall heights and the results were subsequently evaluated and discussed. It was found out that the potential energy from 100 to 230 J are suitable for PP penetration; however, as the optimal 100 J can be considered. Higher heights are not needed because of increasing power consumption of the test device. With regard to deformation and crack growing thus PP is a tough material which is firstly plastically deformed and then on one side there is stress concentration, after that the crack spread around the penetrator. This material can be considered as a suitable material for impact applications from point of view of multiaxial impact load.

Key-Words: - polypropylene, drop-weight tester, sample penetration, impact resistance, impact energy, fall height

1 Introduction

Polypropylene (PP) is a nonpolar thermoplastic semi-crystalline polymer, it is the most consumed polymer globally and has light weight and low density. PP is widely used because of its low cost and being non-toxic and non-hazardous. PP has a great resistance to acids and alkalis, good processing features, electrical insulation, good chemical stability and its bending fatigue resistance is also great. However, PP has low mechanical properties, which is possible to improve by reinforcing with fillers [1, 2].

Siti Rohana Ahmad, Chengzhe Xue and Robert J. Young from United Kingdom dealt with the reinforcement of PP by graphene nanoplatelets (GNP). An average particle diameter of GNP was 15 μm and the average thickness was 6-8 nm. They found out that the blending of GNP to PP led to a huge modification of both mechanical properties and also the microstructure. The thermal stability, the melting temperature and degree of crystallinity were increased. It was found that the Young´s modulus of PP/GNP nanocomposites increased with the loading of GNP [1].

Jia-Horng Lin, Chien-Lin Huang, Chi-Fan Liu, Chih-Kuang Chen, Zheng-Ian Lin and Ching-Wen Lou used as a filler for PP short glass fibres (SGF) and because PP is nonpolar polymer, it was necessary to use a coupling agent for better adhesion between PP and filler. SGF´s average length was 3.2 nm and diameter was 13 μm. This filler was treated with a silane coupling agent. Maleic anhydride grafted polypropylene (PP-g-MA) and maleic anhydride grafted styrene-ethylene-butylene-styrene block copolymer (SEBS-gMA) were used as coupling agents. They blended various amounts of PP, a specified amount of 25 wt% of SGF and 2, 4, 6 or 8 wt% of a coupling agent (PP-g-MA or SEBS-gMA) together to the form different PP/SGF/PP-g-MA blends and PP/SGF/SEBS-g-MA blends and they successfully improved the compatibility between PP and SGF by using previously mentioned coupling agent. The flexural strength, tensile strength, impact strength, compatibility and thermal behaviour were increased. They found out that SGF is a good reinforcing fibre and the connection of 25 wt% of SGF improves the flexural, tensile and impact strengths of PP [2].

Because PP presents low mechanical performance and low impact resistance at temperatures below its glass transition, it is beneficial to create PP blends with elastomeric compounds. The scientists from Mexico dealt with one of these types of blend, namely with PP/EVA (poly[ehtylene-co-(vinyl acetate)]) blend and they studied the effect of compatibilizers on the impact behaviour of this blend. They found out the relationship between the impact resistance and both EVA concentration in the blend and particle size of the dispersed EVA phase. In content of 40 % of

EVA in the blend, the impact resistance increased of more than 270 % with the addition of 6.2 phr of compatibilizers at ambient temperature. Moreover, with increasing the compatibilizer content to 10 phr, an additional rise in the impact resistance was obtained [3].

The scientists Lu Wang and Douglas J. Gardner from USA studied the difference between injection moulded PP samples and PP samples created by fused layer modelling (FLM) device. They used two printing process parameters a layer height and extrusion temperature and explored to examine their influence on the Izod impact strength of printed PP samples. The higher proper printing process control, the more similar Izod impact strength to injection moulded PP is. The higher extrusion temperature and the smaller layer height, the smaller cell sizes and higher degree of diffusion is [4].

Ying-Guo Zhou, Bei Su, Lih-Sheng Turng investigated PP/LDPE blended parts with a chemical blowing agent (CBA). They fabricated super-ductile PP/LDPE blended parts by conventional injection moulding machine with CBA. They found out that PP/LDPE blend tends to create super-ductile parts using the chemical foaming method. They also found out a close relationship between morphological structures which were influenced by the packing pressure and time, dosage of the blowing agent and ratio of the composition and mechanical properties [5].

The Brazilian scientists studied a lignin as a green primary antioxidant for PP and they found out that lignin showed an appropriate dispersion in PP matrix without heterogeneities of the cryogenic fracture surface of test samples. To obtain this dispersion, it is needed to use a twin-screw extruder. They also realized that it is possible to use lignin as a stabilizer for PP exposed to humid and warm conditions [6].

Many other studies are focused on the mechanical behaviour of polypropylene reinforced by the various fillers. The Brazilian scientists compared the natural fibres with glass fibres and they found out that natural fibres have better results in some mechanical properties such as stiffness, flexibility and impact strength, on the other hand, some properties such as the resistance to moisture and compatibility between polymer matrix and fibres were worse compared to glass one [7]. Other Brazilian study dealt with treatment of pineapple fibres and its influence on the mechanical properties of the composites [8]. The mechanical behaviour was also studied in works from USA and India which were focused on PP reinforcement with talc, clay and sepiolite [9, 10].

K. Wang, N. Bahlouli, F. Addiego, S. Ahzi, Y. R´émond, D. Ruch and R. Muller found out that the addition of talc fillers to the PP matrix caused the increase of the thermal stability and melting and crystallization temperature and the crystallinity content, the decrease of the glass transition and the increase of Young´s modulus etc. During the recycling, they added the talc filler, which caused the keeping of the melting and the crystallinity temperature constant and continuously the glass transition temperature of PP decreased [11]. Next study from Canadian scientists dealt with the effect of recycled PP percentage, annealing conditions and glass fibre percentage on the mechanical behaviour of injection moulded PP samples [12].

Our study deals with pure PP and its impact behaviour namely resistance against falling penetrator. There is a small number about research concentrated on pure PP mechanical behaviour which is concentrate on the impact resistance of this material. It is important to know well the mechanical behaviour of pure PP and then it is possible to improve the properties using some filler or some kind of polymer modification. Usually toughness of filled polymers is lower than non-filled polymers; however, it depends on type of filler which will be studied in next research.

2 Problem Formulation

Polypropylene was used as the basic polymer material (TATREN, IM 25-75). An ARBURG Allrounder 470H Advance Injection moulding machine was used for sample preparation, with the processing conditional to comply with polypropylene (PP) producer’s recommendations, as can be seen in Tab. 1. The samples were in the shape of plates with dimensions 100×100×3 mm according to ISO 6603-2.

Injection moulded polypropylene samples were tested on drop weight test machine Zwick HIT230F according to ISO 6603-2 at ambient temperature 23 °C. As a main parameter fall height which was optimized was used. However, for easier explanation in this article impact energy, which is calculated from fall height, weight and gravity acceleration constant was used. Fifteen samples at each height (30, 50, 100, 150, 200 and 230 J) were tested and then values of maximum impact force and all consumed work were statistically evaluated in program TestExpert II and MiniTab. At the end crack growing and deformation of samples after the test of each height were evaluated.

Table 1: Setting of injection moulding machine parameters.

Injection Parameters	**Values**
Injection Pressure [MPa]	70
Injection Velocity [$mm.s^{-1}$]	50
Holding Pressure [MPa]	60
Cooling Time [s]	20
Mould Temperature [°C]	30
Melt Temperature [°C]	225

Fig. 1. Falling-dart system [13].

1 – Test specimen; 2 – Hemispherical striker tip 10 mm; 3 – Force sensor; 4 – Shaft; 5 – Test specimen support; 6 – Clamping ring (optional); 7 – Base; 8 – Acoustic isolation (optional); 9 – Stand for falling-dart system; 10 – Holding and release system for weighted striker; 11 – Guide shaft for weighted striker; 12 – Weighted striker 23,77 kg.

3 Problem Solution

This study is concentrated on optimization of fall high during drop weight test of PP. Injection moulded PP samples were penetrated by penetrator with fall heights in the range from 30 to 230 J and the results were subsequently evaluated. The conditions of injection moulding are displayed in Table 1, PP statistical evaluation of the maximum force measurements is shown in Table 2 and PP statistical evaluation of the all consumed work at the height of the fall is displayed in Table 3.

Table 2. PP statistical evaluation of the maximum force at the height of the fall.

Set energy of fall [J] / **Statistical characteristics [N]**	**30**	**50**	**100**	**150**	**200**	**230**
Number of measurements	15	15	15	15	15	15
Arithmetic mean	3296	3556	3716	3768	3820	3850
Type error A	1	4	4	8	5	5
Standard deviation	5	13	12	24	16	16
Minimum value	3289	3540	3701	3728	3804	3822
Median	3296	3553	3712	3773	3813	3851
Maximum value	3304	3578	3739	3801	3844	3868
Variation range	14	38	38	73	40	47

Table 3. PP statistical evaluation of the all consumed work at the height of the fall.

Set energy of fall [J] / **Statistical characteristics [N]**	**30**	**50**	**100**	**150**	**200**	**230**
Number of measurements	15	15	15	15	15	15
Arithmetic mean	31,9	58,5	62,5	61,7	61,2	61,4
Type error A	0,0	0,3	0,2	0,3	0,2	0,4
Standard deviation	0,1	0,9	0,6	0,9	0,8	1,1
Minimum value	31,8	57,1	61,5	60,4	59,8	60,0
Median	31,9	58,4	62,4	61,5	61,1	61,2
Maximum value	32,0	59,8	63,4	63,1	62,4	63,2
Variation range	0,2	2,7	2,0	2,7	2,6	3,3

3.1 Maximum impact force

The height of fall was set at all measurements differently and the results are then discussed.

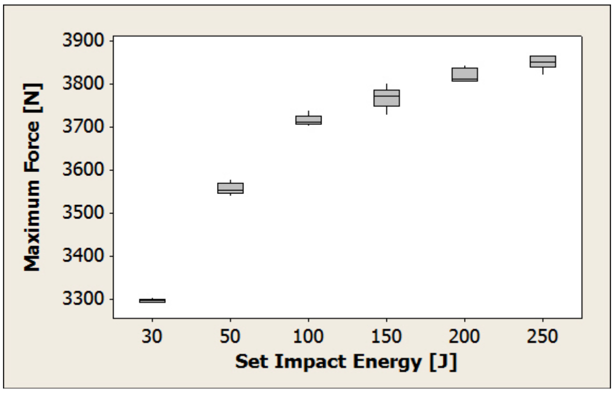

Fig. 2. PP Boxplot graph of maximum force at fall height.

In Figure 2 the maximum force at fall height is displayed. At the height of 30, the sample was not penetrated, there just plastic deformation occurs. It is probably caused by too small fall height for penetration of this material. Penetration occurred at 50 J, but the force is smaller than at the material with the higher fall height what can be caused by the friction of the penetration along the material. Because of that the value 100 J looks like the optimal fall height, because there the penetration occurs and the variation range is smaller than others. At the set impact energies from 150 to 230 J the penetrations are also, but it is not needed to use these heights because of increasing power consumption of the test device.

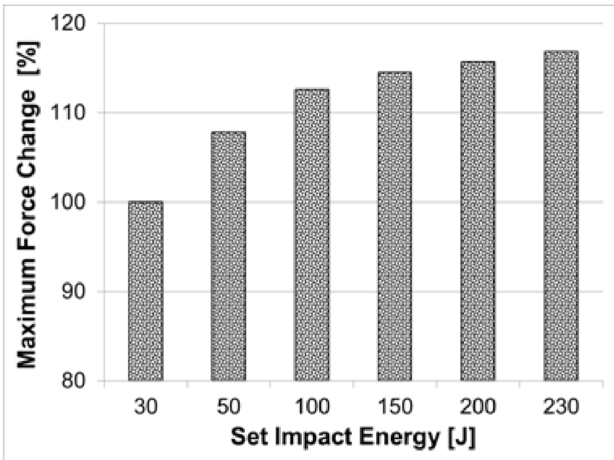

Fig. 3. PP percentage change in maximum force to the prescribed base energy of fall 30 J.

The force change in % during the test can be seen in Figure 3. The changes move in 17 % from the sample with no penetration to last penetrated sample. The sample with the optimal fall height 100 J in comparison with the first penetrated sample at 50 J shows the change around 6 %. The last penetrated sample´s height 230 J increases by 4 % in comparison with the sample with the optimal fall height 100 J.

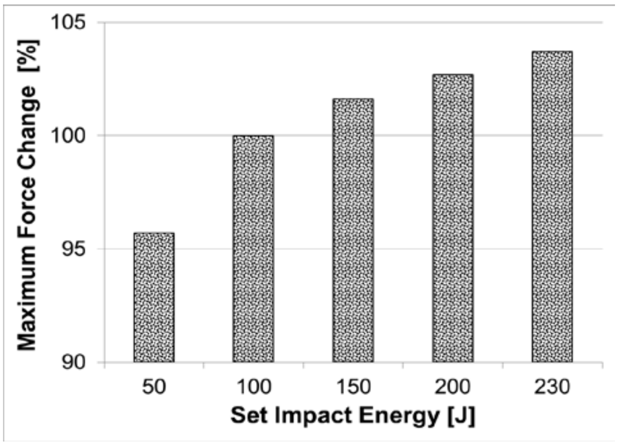

Fig. 4. PP percentage change in maximum force to the prescribed energy of fall 100 J.

In Figure 4 it is possible to see how the force changes in comparison with 100 J. The force is subsequently increasing. The first penetrated sample at 50 J has lower force change by almost 6.5 % in comparison with the highest impact energy 230 J. From the value 100 J it is clearly visible that the force is slightly increasing up to 3.5 % at the impact energy 230 J. From this evaluation is possible to sum that the value 100 J seems to be the optimum value because of its smallest variation range and standard deviation.

3.2 All consumed work

The consumed work was measured at each adjusted impact energies and the results from the measurements were subsequently discussed.

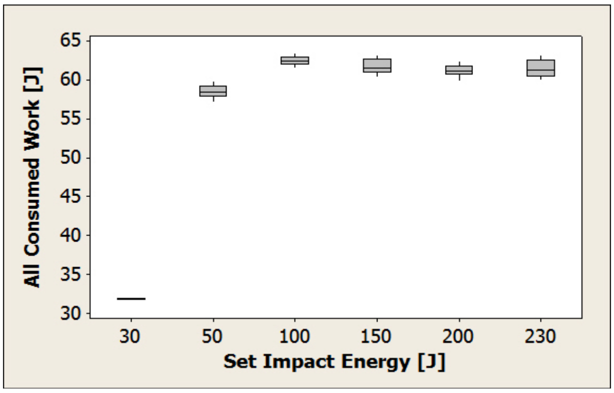

Fig. 5. PP Boxplot graph of all consumed work at fall height.

All consumed work at set impact energy is displayed in Figure 5. The impact energy 30 J clearly shows that there is no penetration, because of that the consumed work is lower significantly than at others higher used energies. From the set impact energy 50 J the penetration occurs in all cases up to 230 J. From the boxplot graph is clear that the optimum impact energy is 100 J. It has the smallest variation range and it is enough high energy for penetration of the sample. The energy 50 J seems to be enough, but there is the higher standard deviation and also the variation range. The energies from 150 to 230 J are not needed to use, because there are just smaller differences in consumed work, but there are higher variation ranges.

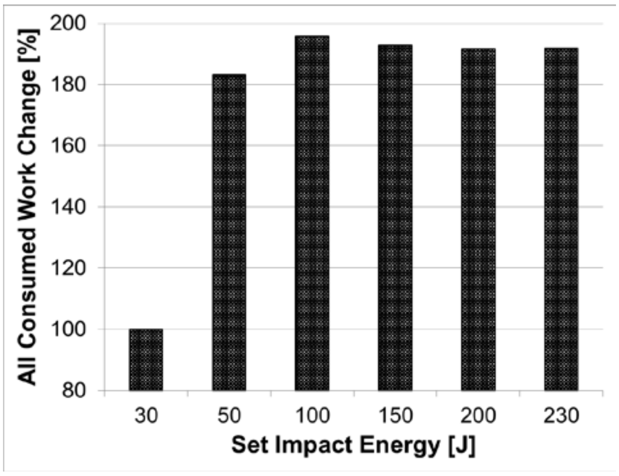

Fig. 6. PP percentage change in all consumed work to the prescribed base energy of fall 30 J.

Figure 6 points out the consumed work change in % and at the prescribed impact energy 30 J the sample penetration did not occur. The value 50 J is in comparison with 30 J much higher, more than by 80 % and that is the first value, where the penetration occurred, but due too high variation range, the set impact energy 100 J seems to be the optimum energy as it was mentioned above. The fall heights from 150 to 230 J are similar; however, there is slightly decreasing tendency, but their variation ranges and standard deviations are higher than in the case of the fall height 100 J.

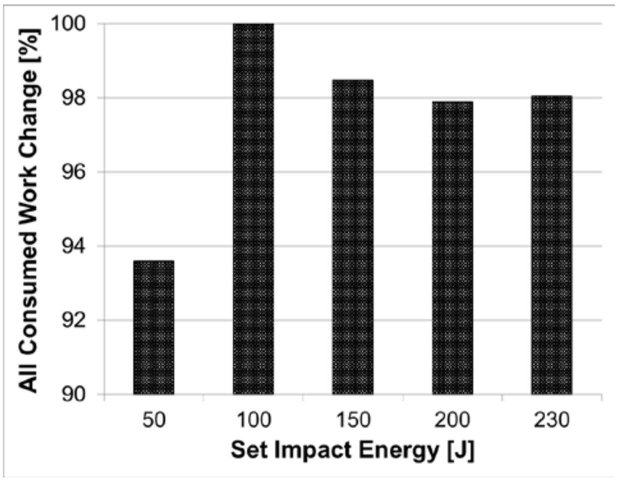

Fig. 7. PP percentage change in all consumed work to the prescribed energy of fall 100 J.

The detail point of view on the consumed work change from the first value where the sample penetration occurred is in Figure 7. The difference between the optimum value 100 J and 50 J is almost by 6.5 %. The set impact energy 230 J has in comparison with 100 J lower consumed work by 2 %. As it was written above optimum set energy seems 100 J from statistical view (the smallest variation range and standard deviation); however, at least the same importance has observation of deformation, especially crack growing.

3.3 Crack growing and sample deformation after the test

During the drop weight test, the impact force was recorded depending on time and after the drop weight test the samples were photographed for a better idea about the deformation. Scanning of the current impact force was recorded by piezoelectric sensor with frequency 1 MHz. This sensor is sensitive and accurate for recording data. Subsequently crack growing and deformation was evaluated in software testExpert II which is useful tool for statistical evaluation and describing of measured graphs.

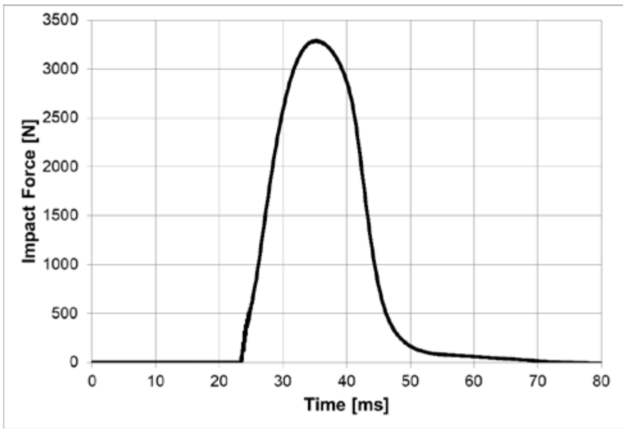

Fig. 8. Impact force record from drop-weight tester for PP at set impact energy 30 J.

Figure 8 shows that the maximum value of the impact force at the impact energy 30 J is 3 304 N, in this case the penetrator stopped in the material and the whole energy was absorbed and changed into the plastic deformation of the sample and heat, it means that there was no penetration recorded. In this case material can be used as applicable up to 30 J without penetration at multiaxial impact load.

Fig. 9. PP deformation after drop weight test at 30 J.

In Figure 9, there is a view from the top on the plate shape sample and there is also clearly shown that the material was not penetrated, there is only the plastic deformation with no penetration. Hemispherical shape from the falling penetrator is imprinted into PP material as can be seen in the middle of the picture.

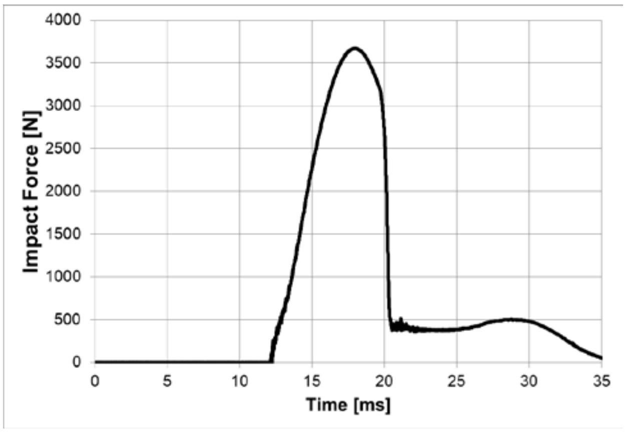

Fig. 10. Impact force record from drop-weight tester for PP at set impact energy 100 J.

From Figure 10 it is possible to see that the penetrator touched of surface at 12.2 ms then PP is deformed under multiaxial impact load. In time 18.3 ms maximum impact force 3650 N was recorded, after that impact force dropped down at 380 N in time 20.6 ms where is expected beginning of growing crack.

Fig. 11. PP deformation after drop weight test at 100 J.

As is visible in Figure 11, the penetrator passed through the sample. As it was written above in time 20.6 ms start to crack on one side then crack is going around the penetrator to open the top of the material. After material dodges on maximum position come pulling the penetrator from material, during the reverse movement, the top of the crack is again closed.

4 Conclusion

In this study the injection moulded PP samples were subjected the test of falling penetrator at different fall heights, which was counted on potential energy. The range of set impact energy was from 30 to 230 J. At the value of potential energy 30 J the sample was not penetrated because of too small fall height. The sample was just deformed under impact load, after the test there was hemispherical deformation which was caused by the shape of penetrator. All set energy was transformed on mechanical work (deformation of sample) and heat.

The value 50 J was the first set energy where the sample penetration occurred but there was a smaller impact force and all consumed work, which was measured and statistically evaluated, than it was expected which could have been caused by the friction of the penetrator along the material during the test. Each higher set energy up to 230 J, which was the highest used energy in this study, the material penetrated; however, the values from 150 to 230 J are not needed to use because of increasing power consumption of the test device.

The conclusion of this study is that the potential energy 100 J can be considered as an optimal for the penetration test of PP material; nevertheless, it is not possible to use it as a general information for usage of drop-weight tester for the group of polypropylenes which constitutes a lot of types with different mechanical properties, because of some kinds of modifications.

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