



Effect of oven residence time on mechanical properties in rotomoulding of LLDPE

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Abstract. In rotational moulding of plastics, improving the mechanical properties without sacrificing the processibility is a challenging task. In this paper, an attempt has been made to investigate the effect of oven residence time on the mechanical properties of the rotationally moulded products made using linear low density polyethylene. Simulation studies were conducted using ROTOSIM software to analyze thermal transitions and phase changes during the process. Degree of curing of the polymers was also assessed and correlated with mechanical properties. Experiments were further conducted to obtain favourable oven residence time to obtain highest mechanical properties. Experimental investigation revealed that there exist regions where the part was ‘under-cured’ and mechanical properties were found to be inferior. It was also found that when parts were ‘over-cured’, the mechanical properties were severely affected. A regime of favourable processing window was identified where the highest tensile, flexural and impact properties were noticed.

Keywords. Rotational moulding; oven residence time; LLDPE; mechanical properties; degree of curing; degradation.

1. Introduction

Rotational moulding is a polymer processing method used to produce hollow parts, usually of large volume. Since the polymer melt is not forced to take up a shape of the mould, the parts produced by this process are relatively stress-free as compared to other moulding processes like injection moulding or blow moulding. With proper product design, parts assembled from several pieces can be moulded as a single part (with no weld lines or joints), eliminating high fabrication and assembly costs. The products obtained from rotational moulding find extensive applications in various fields like agriculture, storage tanks, industrial equipment, medical devices, material handling, road/highways, and automobiles

Rotational moulding process is carried out in four different stages. These include charging the mould with thermoplastic powder [usually linear low density polyethylene (LLDPE), of around 500 µm average particle size], heating and melting of the powder in a biaxial rotating mould, cooling of the mould and de-moulding of the part at slightly higher temperature than the ambient conditions [1–4]. The mechanical properties of rotationally moulded parts like tensile strength, impact strength, and flexural strength are the key measures of quality of the product. The mechanical properties in turn depend on

several process parameters like raw material [melt flow index (MFI), density, powder particle size, etc.], material of the mould, rotational speed and speed ratios of the mould, oven residence time, cooling time, pigments and additives. [5].

Crawford [5, 6], Crawford and James [4] identified the peak internal air temperature (PIAT) of LLDPE (200–220°C) as one of the crucial factors to get the highest mechanical properties of the rotationally moulded product. Also, the structure-property-processibility studies of rotational moulding process have been extensively investigated by Crawford [4, 7]. He also tested the rotomouldability of different resins like plastisols, polyethylene, polycarbonate, acetate butyrate, polyamide, elastomers, polyurethane, polypropylene, ethylene vinyl acetate, fluorocarbons and even polyamides. Out of these, LLDPE resins have the largest consumption in rotational moulding industry. It is due to their ideal melt flow property, broader processing window, excellent thermal stability and good mechanical properties. For PP/LLDPE blends, Run *et al* [8] revealed that the processing temperature greatly affects the mechanical properties, especially the ductility and the impact strength. Recently Aissa *et al* [9] have followed the motion of polymer powders inside a spherical mould to determine the effect of polymer powder particle size and distribution using gray-level co-occurrence matrix technique.

Ramkumar *et al* [10] have presented an extensive review on mechanical and fracture characterization of LLDPE.

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Sintering process of LLDPE has been investigated by Spence and Crawford [11]. The investigation revealed that increasing the number of fine particles causes formation of bubbles that were physically smaller, while larger particles increase the porous area in a product. Pick and Jones [12] found that metallocene-LLDPE (having a narrow molecular weight distribution than LLDPE) exhibit better impact properties than conventional LLDPE. Peroxides were used to obtain mouldings from LLDPE by chemical cross-linking of foams with uniform cell distribution and higher melt strength [13]. These were found to have good impact resistance, even at longer processing times.

Alejandro *et al* [14] have investigated the effect of pro-oxidant additive on LLDPE and LDPE and found complete loss of mechanical properties at different exposure times.

Waigaonkar *et al* [15] found that the cooling rate governs the crystalline morphology of the polymer which in turn governs the impact performance of the product.

Several researchers adopted simulations to understand the complex nature of heat transfer during the rotational moulding process. Antonio and Alfonso [1] used statistical and kinetic models for one-dimensional unsteady heat transfer during rotational moulding. Source based formulation was proposed by Banerjee *et al* [16] for modelling layer by layer non-isothermal deposition of plastic. The proposed method was also used for calculating the cycle time for particulate composites. A multimode crystallization kinetics model was suggested by Glomsaker *et al* [17] to correlate the crystallization with warpage. Recently, computer simulation based prediction of internal air temperature and degree of curing in multilayer rotational moulded parts was investigated by Alongkorn [18] using ROTOSIM simulation software.

In rotational moulding process, cycle time is observed as an important process parameter by the researcher which affects the quality of the product. Cycle time implies the total time spent by the polymer inside the oven (heating and cooling) till the complete product is demoulded. Tan *et al* [19] have found that the water cooling could be an effective alternative to reduce the cycle time in comparison with introduction of compressed air inside the mould as well as the use of CO₂ at cryogenic conditions. According to the authors, cycle time has been reduced by using polyethylene of reduced molecular weight or melt viscosity. However, this can result in inferior impact strength [2]. Abdullah *et al* [20, 21] have reported a cycle time reductions of up to 70% with combination of different conditions like surface enhanced moulds, higher oven flow rates, internal mould pressure, and water spray cooling for cycle time reduction in rotational moulding. Liu and Fu [22] found that the mould surface enhanced with fins had faster heating and cooling rates and that triangular fin could be considered as a better choice from the manufacturing perspective. Several other innovative attempts have been made to reduce the cycle time, which include changing the thermal

characteristics of the shell material [23], introducing internal pressure [24], and employing internal cooling [25].

From the above literature survey, it is evident that oven residence time is one of the most important process characteristics that govern the thermo-mechanical properties of the rotationally moulded product. As oven residence time is the time spent by the polymer inside the oven from room temperature till the oven is switched off, it also has deep impact on the productivity of the process. As rotational moulding process is mainly used to produce hollow products of larger dimensions the experimentation on industrial scale needs considerable resources and time, though the simulation studies are helpful in such situations very few of them take into account actual process conditions and their effect on mechanical properties of the product in their prediction. As a consequence, many times the prediction differs from the shop floor conditions. This paper deals with simulation and experimental studies to evaluate the effect of oven residence time on the mechanical properties of the rotationally moulded product. The simulation studies were initially conducted for different oven residence time and the extent of curing of the part was determined using ROTOSIM simulation software. The extent of curing, also referred as 'degree of curing', is a major factor in determining the mechanical properties of the component assessed using ROTOSIM. Experiments were further conducted to verify the predictions and obtain the conditions for favourable oven residence time to get the highest possible mechanical properties of the product.

2. Simulation

Rotational moulding process is characterized by the complex nature of heat transfer involving several phases and density changes of polymer. Moreover, the phase changes occur over a range of temperature. Further, due to the bi-axial nature of mould rotation, there is a dearth of accurate thermal data measurement techniques and equipment at lesser cost [26]. This necessitates reliable prediction of critical timings of the process like switching off the oven and de-moulding time. The prediction can also economize the energy inputs to the processes and save significant energy as well as time. ROTOSIM software takes into account all the possibilities that exist in a typical rotational moulding process. Hence, the simulation studies were conducted using ROTOSIM.

ROTOSIM is a computer program for simulating the processes that occur in a rotational moulding cycle for polymers. It is based on a complex mathematical model of the major physical processes in the cycle. It enables the user to experiment with a variety of different operating conditions and observe the effects that these have on the resulting cycle conditions and the moulded product. During the simulation run, building up of a melt layer on the mould

surface and development of solidified polymer layer can be observed. Temperature and phase change with respect to time are also generated by the simulation. The different aspects of the simulation are given below.

2.1 Solid model of the mould and meshing

For this study, a hollow product used as a plant vase has been selected which can be easily produced on a lab scale rotational moulding machine. An aluminium (Al) mould of 3 mm thickness has been considered, the shape of which resembles an inverted frustum of a cone. In order to have sufficient stiffness of the product, a minimal wall thickness of around 2 mm was designed. The part was initially modelled using Pro-E Wildfire software and meshing and analysis is done in ROTOSIM. The solid model of mould was meshed with triangular elements. Meshed model of the mould is as shown in figure 1.

2.2 Material properties and process conditions

In this study, LLDPE was considered for the purpose of simulation which was also utilized for experimental work. The mould and material properties are given in table 1.



Figure 1. View of the meshed mould.

For rotational moulding process, a biaxial mould rotation was selected with the arm and plate speeds as 8 rpm and 2 rpm respectively, resulting in a major to minor axis ratio of 4:1, (which is considered to be ideal for getting uniform wall thickness) [5]. Initial conditions for simulation and experimentation were taken as 30°C, while demoulding temperature was assumed as 50°C.

For simulation studies, the temperature profile around the mould is an important input which must bear resemblance to the actual temperature around the mould. Thus, to correlate the findings with the experimental conditions, the mould temperature was measured (details given in section 3.2) and the mould environment profile was generated as shown in figure 2. This profile served as an input to ROTOSIM. The profile shows a time period of around 1680 s (almost 28 min) to reach to peak set temperature of 220°C. The temperature is held constant at 220°C from 1680 to 1780 s using ON-OFF relays as shown by the points B-C in figure 2. The oven residence time from 32 to 44 min has been considered in this study. In simulation, this can be realized as an increase in the length B-C in figure 2. The other features like speed reversal of the mould and internal cooling of the mould were not taken into account in this study. The outcomes of this simulation studies were compared with those obtained from experimental studies and discussed in the results and discussion.

3. Experimental details

3.1 Materials

For this study, LLDPE of grade R350 A 42, which has an MFI of 4.2 g/10 min and a density of 935 kg/m³ manufactured by Gas Authority India Limited (GAIL) was used. The average particle size of the powder was 500 µm (around 35 mesh number). This grade is normally recommended for manufacturing of water storage tanks, automobile parts, boats, etc. The powder was already mixed with antioxidants and UV stabilizers, which turned its colour from natural to black. Based on the volume of the mould, powder shot weight of 0.6 kg was used in order to produce moulding with a wall thickness of about 2 mm. The internal mould surface of the aluminium mould was coated with a silicone oil based mould release agent manually.

Table 1. Base case moulding conditions.

Moulding condition	Mould (aluminum)	LLDPE	Air
Thermal conductivity (W/m K)	204	0.25	0.025
Specific heat of (J/kg K)	896	2600	1006
Density (kg/m ³)	2707	749.6 (melt)	1.205
Internal convective heat transfer (W/m ² K)	–	–	5
External air convective heat (W/m ² K)	–	–	20

3.2 Machine and mould

A lab scale electrically heated bi-axial rotational moulding machine was used as shown in figure 3. An aluminium hollow mould having the shape of an inverted frustum of cone was used for getting the desired product. This resembles to the solid model generated in section 2.1. A few preliminary experiments were initially conducted to decide the regime of oven residence time and assess the internal air temperature of the mould. In all the trials, oven

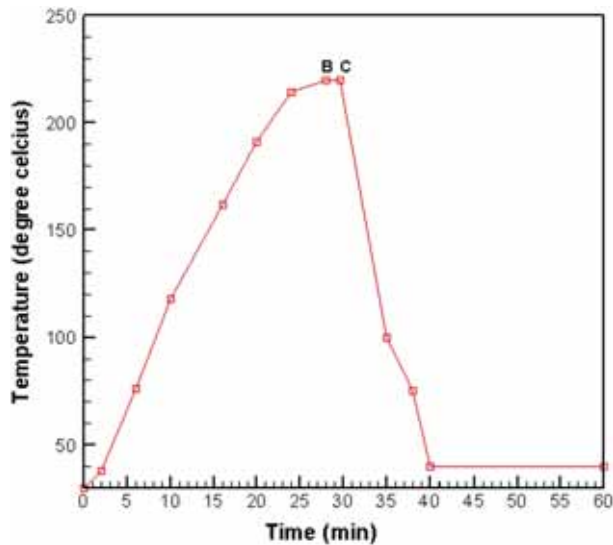


Figure 2. Typical mould environment profile.

temperature was set at 220°C. From the preliminary experiments, the oven residence time from 32 to 44 min was chosen as the active regime of experimentation. The internal air temperature was measured using a K type thermocouple considering uni-axial rotation of the mould as with this setup it is not possible to measure the same bi-axially. It was confirmed that this temperature was sufficient to get a PIAT of 200°C in the above time regime.

During these experiments biaxial mould rotation was used with the arm (major axis) to plate (minor axis) speed ratio maintained at 4:1 to get consistent wall thickness. Table 2 gives details of the experimental set-up. With the chosen regime, experiments were conducted by altering the oven residence time and the product was obtained. The products were tested for mechanical properties in terms of tensile, flexural and impact strengths.

3.3 Testing of mechanical properties

The test specimens were prepared according to ASTM D 638 for tensile, ASTM D 790 for flexural and ASTM D 256 for impact testing respectively. CNC engraving machine was used to cut the required contour. Bench universal testing machine was used for tensile testing. Load cell of 14.7 kN was used along with a crosshead speed of 5 mm/min. For the flexural testing, the load cell of 0–2.5 kN was used and flexural strength at yielding was obtained. Impact tests were performed in typical Izod impact testing machine. A pendulum of maximum energy capacity of 4 J was used to evaluate the energy absorption ability of the

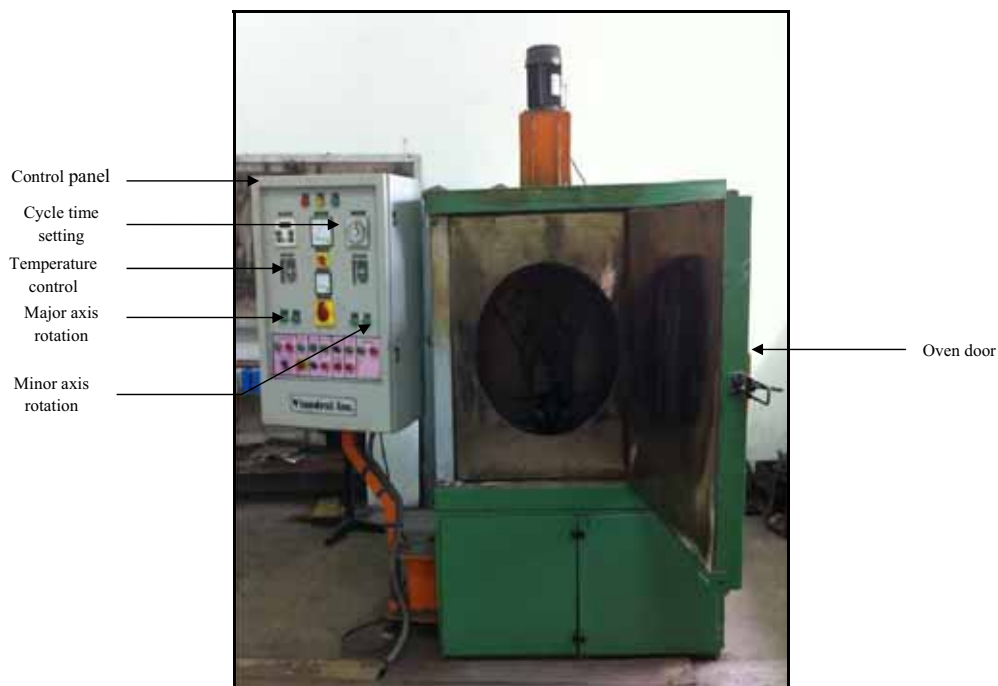


Figure 3. Biaxial rotational moulding machine.

Table 2. Experimental setup used for the work.

Rotational moulding machine specification	Model: clamshell type single arm biaxial machine
	Method of heating: electrical Control voltage: 220V Power rating of oven: 8 KW Power rating of blower: 0.37 Speed ratio: (major axis:minor axis) 4:1 Drives: 0.5 HP Variable frequency drive Temperature range: 30–250°C Maximum mould dimension: 300 mm × 300 mm × 300 mm
Mould specification	Material: aluminum(Al) Shape: inverted frustum of a cone Release agent: Metrork silicone 17 compound Dimensions: Top diameter: 300 mm Bottom diameter: 150 mm Height: 220 mm
Raw material specification	Material: R350 A 42 LLDPE supplied by GAIL India MFI: 4.2 g/10 min Density: 935 kg/m ³ Shot weight: 0.6 kg
Testing equipment	Tensile and flexural testing: Machine: universal testing machine Load cell: 14.7 kN Cross head speed of 5 mm/min Impact testing Izod impact tester with 4 J pendulum.

material. To account for process variability during experimentation, three replications were taken for each experimental run. Thus, three samples of each tensile, flexural and impact specimens were cut and subjected to testing.

Table 3 shows the plan of experiments, the value of tensile, impact and flexural strength obtained for different oven residence times.

4. Results and discussion

4.1 Tensile strength

The stress–strain plot for oven residence time of 38 min is as shown in figure 4. The plot clearly reveals that elastic region at very low strains and significant plastic deformation are the characteristics of thermoplastic materials like LLDPE. The ultimate tensile strength was found as 17.4 MPa. Similarly, stress strain plot for all the oven residence time were recorded and the variation of tensile strength with respect to increase in oven residence time is shown in figure 5. These results reveal that tensile strength gradually increases as the oven residence time increases from 32 to 40 min and falls after 40 min. A closer look into the process gives more insight into this phenomenon. As the temperature increases from room temperature (30°C), the powder inside the mould tumbles and when the temperature is above 120°C the powder starts sticking to the mould surface. With further increase in temperature, coalescence between the powder particles takes place and it becomes loose porous mass. In order to get the highest mechanical properties, the PIAT of the mould should reach 200°C as specified earlier. In the present case, though a PIAT of 200°C was achieved, the molten mass spent a short duration of time at and above 200°C. This resulted in an incomplete fusion of the polymer particles resulting in a non-homogeneous structure, including entrapment of irregularly shaped air pockets. Therefore, it is obvious that the tensile strength was less between 32 and 34 min of oven residence time. This is referred as ‘under-curing’ and resulted in a weak product.

As the oven residence time was increased from 36 to 40 min, the polymer melt spent sufficient time in the oven. Under this condition, the irregular pockets of trapped air transform into spheres. Most of the trapped spherical bubbles disappear and a complete coalescence with homogeneous structure is achieved. This region can be referred as ‘completely cured’ region and results in a good tensile strength of the product. Further, when the oven residence time was increased above 40 min the tensile strength of the product was decreased, as the degradation of the polymer

Table 3. Experimental run and corresponding outputs.

Oven residence time (min)	Average tensile strength (MPa)	Average impact strength (J)	Average flexural strength (MPa)
32	16	0.52	18.2
34	16.2	0.69	18
36	17.2	0.92	17.6
38	17.4	0.97	17
40	17.4	1	17.2
42	16	0.8	16.7
44	15.3	0.6	16.0

was noticed at this stage. This is referred as ‘over-cured’ and results in a partially burnt product.

In order to correlate the mechanical behaviour of LLDPE with that of oven residence time, differential scanning calorimetry (DSC) was performed to characterize the material with a steady temperature rate of 10°C/min. The DSC graph is as shown in figure 6. It shows an endothermic peak at 124°C revealing melting of LLDPE. The material shows excellent thermal stability after melting till a temperature of 249°C. The exothermic peak at 249°C shows the commencement of degradation of the polymer. The peaks after 400°C indicate complete burning of LLDPE including additives. Since the oven heating rate in the rotational moulding set-up is about 5°C/min, the

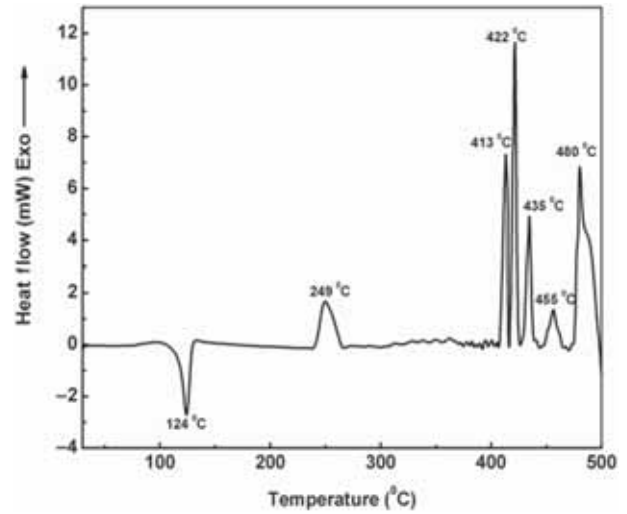


Figure 6. Differential scanning calorimeter (DSC) trace for LLDPE.

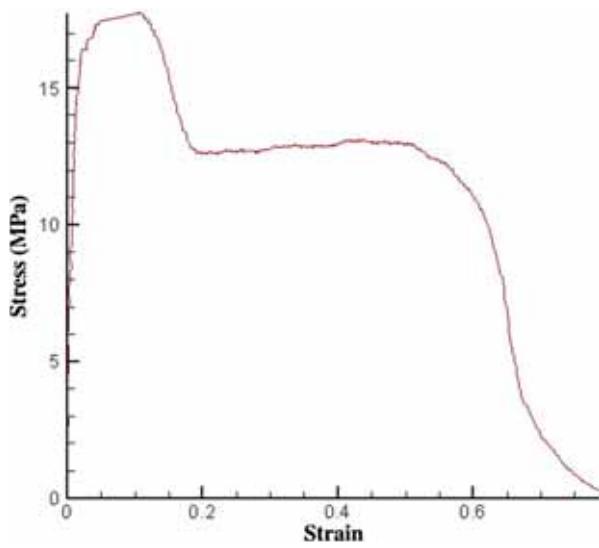


Figure 4. Stress strain plot for oven residence time 38 min.

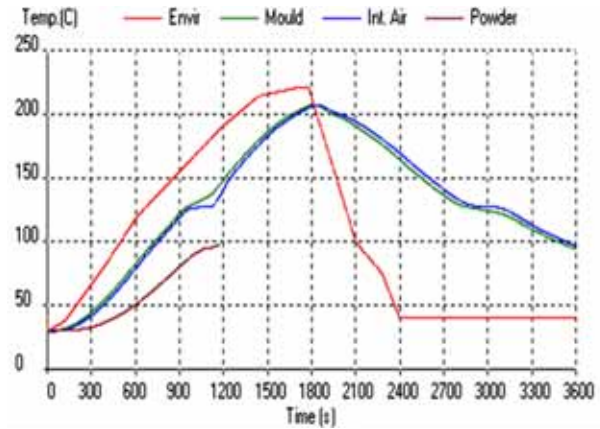


Figure 7. Temperature plot for 32 min.

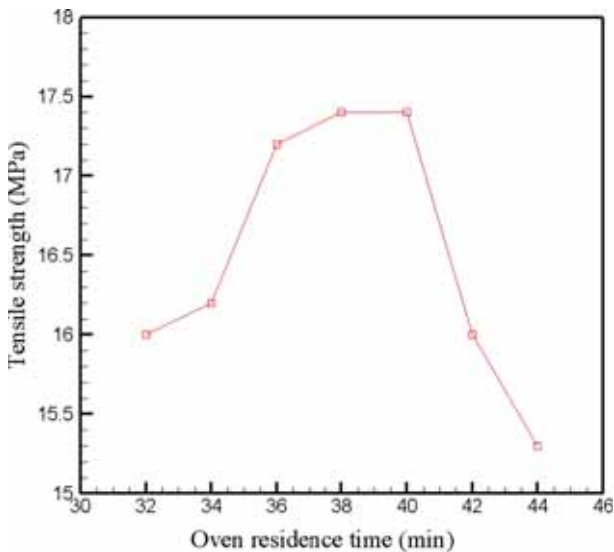


Figure 5. Variation of tensile strength with respect to cycle time.

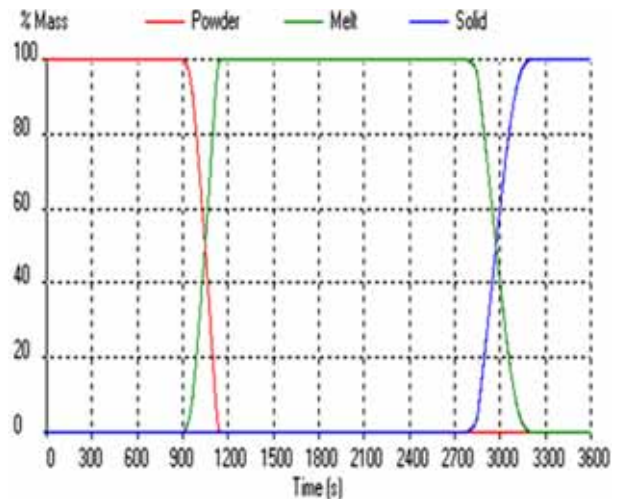


Figure 8. Polymer phase transitions plot for 32 min.

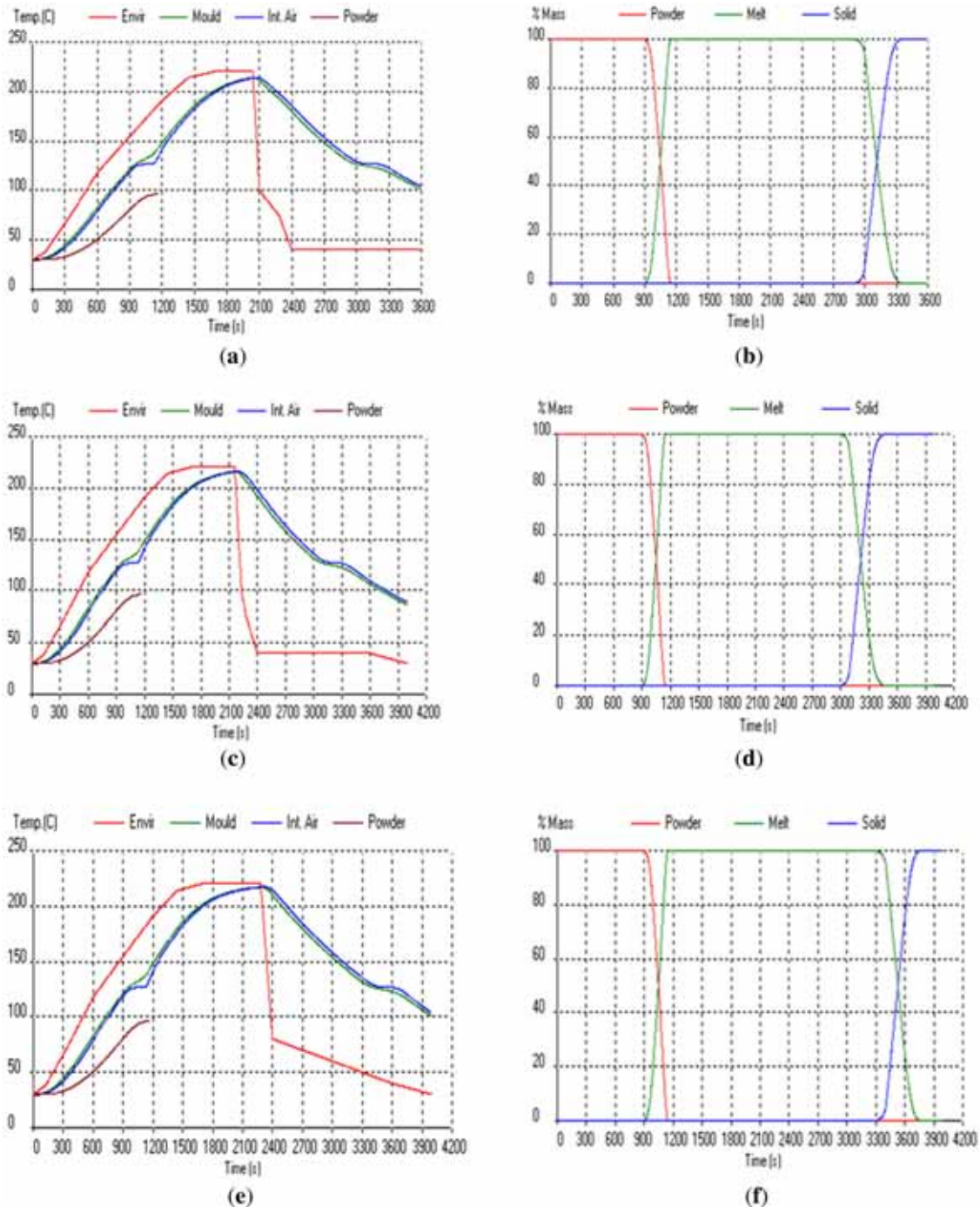


Figure 9. (a) Temperature plots for 34 min, (b) polymer phase transitions plot for 34 min, (c) temperature plots for 36 min, (d) polymer phase transitions plot for 36 min, (e) temperature plots for 38 min, (f) polymer phase transitions plot for 38 min, (g) temperature plots for 40 min, (h) polymer phase transitions plot for 40 min, (i) temperature plots for 42 min and (j) polymer phase transitions plot for 42 min.

decomposition temperature of polymer is realized after 40 min. This resulted in a decrease in tensile strength of the product.

The simulation studies conducted in section 2 provide further insight into the transient temperature distribution inside the mould, which can be correlated with the

mechanical properties of the product. The transient temperature distribution of the process is shown in figure 7, while the polymer phase change plot is depicted in figure 8 for 32 min of oven residence time. From these plots, the time lag due to convective heating from oven (environment) to the mould can be clearly seen. The internal air

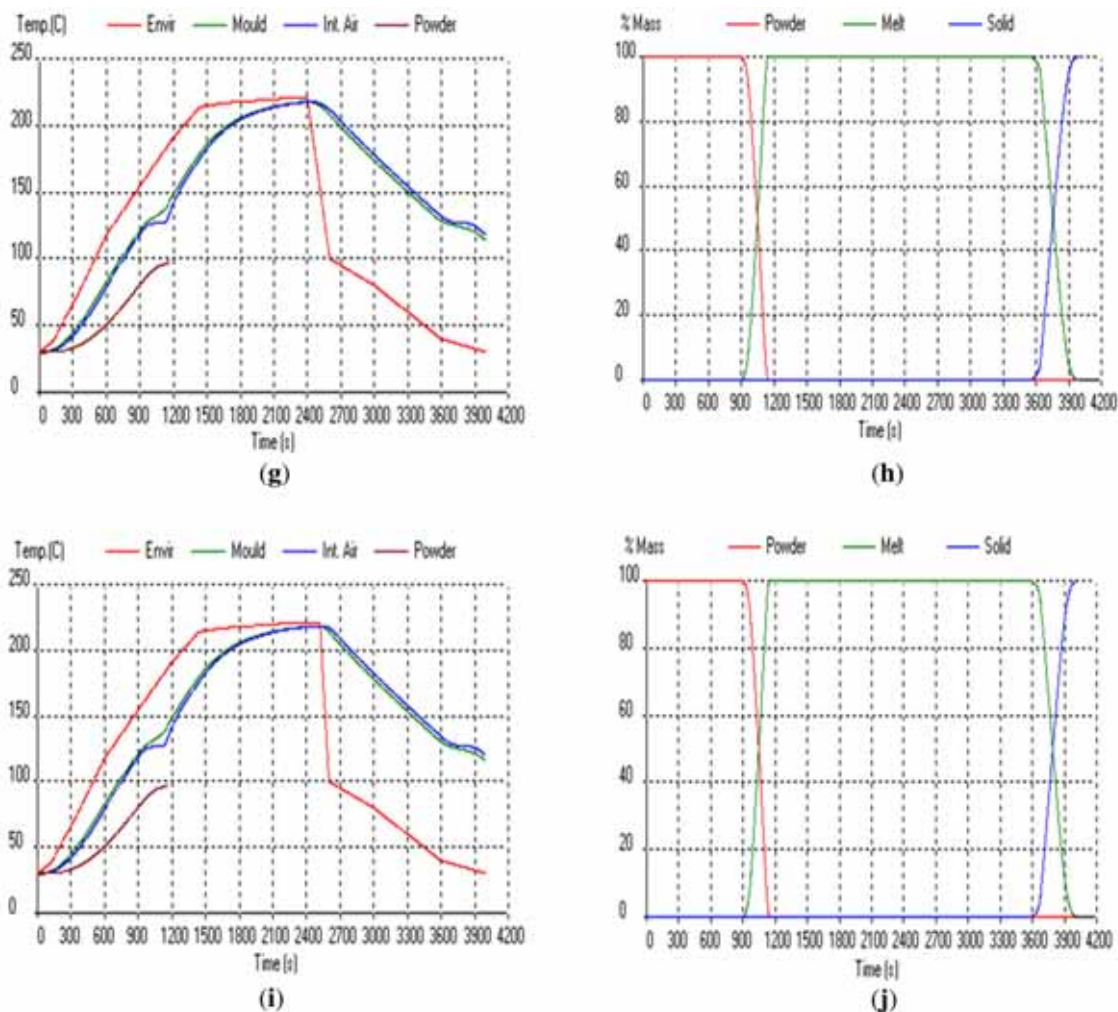


Figure 9. continued

temperature plot (IAT) follows the phase changes in LLDPE. For example, in figure 7, we can notice a horizontal line at around 124°C (15 min), indicating the phase change of the polymer from the powder to the melt. This can also be seen from the phase change plots of the polymer as shown in figure 8. At 15 min the polymer starts converting into melt thereby increasing its mass fraction. At the same time, since the powder is being converted into melt, its mass fraction decreases. It can be noticed from figure 8 that at around 20 min all the powder gets converted into melt and thereafter polymer remains in the molten state. From figure 7, it can be seen that even after switching off the oven at 30 min (220°C), the IAT keeps on rising and it reaches 200°C which is a PIAT of the polymer processed. At 45 min, the molten LLDPE again starts losing the latent heat of fusion and gets converted into solid phase. Thus, complete solidification occurs at around 53 min (100% solid, 0% melt) as evident from figure 8. Therefore, we could notice from this simulation that PIAT of 200°C could be reached in this setting, which was generally considered

as a healthy sign to get better mechanical properties of rotationally moulded products. However, LLDPE has spent around 3.5 min (1750–1950 s) at this temperature, which has caused under curing of the product, resulting in lower tensile properties.

Simulations were further continued by varying the oven residence times starting from 32 min to 44 min keeping other parameters constant. The temperature and polymer phase transitions plots of these are as shown in figure 9(a–j). We can observe that for 34 min, the molten mass is above PIAT of 200°C for 5.8 min, for 36 min it is 8.3 min, for 38 min it is 9.1 min, for 40 min it is 11.6 min, for 42 min it is 13.3 min and so on. In order to represent the extent of time which LLDPE has spent above the melting temperature, time–temperature curves are plotted. These are referred as degree of curing plot. Degree of curing is the time that polymer powder spends in the oven above its melting temperature (125°C in the present case). Thus, higher the degree of curing better is the chances for dissolution of bubbles and getting a sound product. Degree of

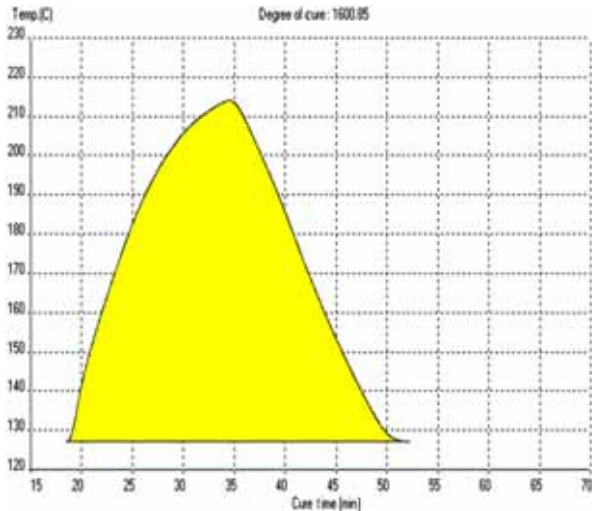


Figure 10. Degree of curing plot for 38 min.

curing plot for oven residence time of 38 min is as shown in figure 10 for reference. Similarly, degree of curing plot can be generated for different oven residence time using simulation, from the simulation it is observed that higher degree of curing is achieved when the oven residence time is increased. Theoretically, though the higher degree of cooling means better mechanical properties, polymer degradation starts beyond a specific temperature (249°C, as confirmed by DSC), which results in reduction in mechanical properties. The results summarized in table 4 clearly indicate the influence of oven residence time, degree of curing and time for which the material is above 200°C on the tensile and flexural strengths of LLDPE. Thus, it can be concluded that not only PIAT but also the time that the polymer spends above the PIAT governs the mechanical properties of the rotationally moulded products.

4.2 Flexural strength

The results of flexural testing are shown in figure 11. These results reveal that the flexural strength of the product decreases as the oven residence time increases from 32 to 38 min. It can be attributed to the incomplete coalescence

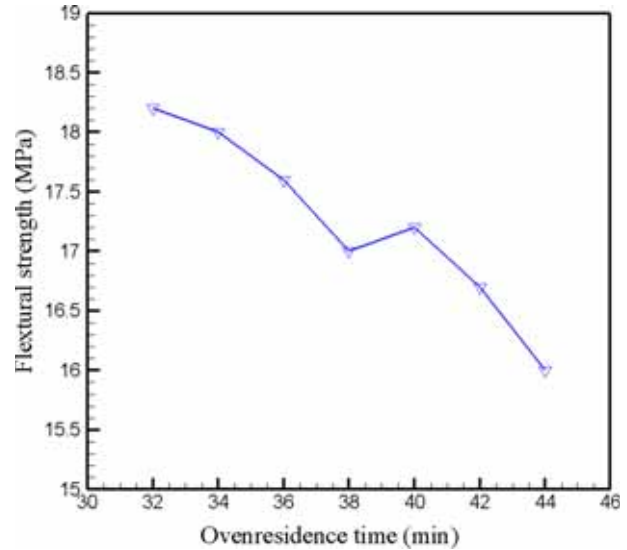


Figure 11. Variation of flexural strength with respect to cycle time.

of powder particle. Such a part can have entrapped bubbles, leading to reduction in flexural strength. With the further increase in oven residence time from 38 to 40 min, the entrapped bubbles may escape owing to reduction in polymer melt viscosity thereby increasing the flexural strength. Beyond 40 min, the product is subjected to oxidation and it becomes brittle. Therefore, the flexural strength is further reduced.

4.3 Impact strength

Variation of impact strength with respect to the oven residence time is as shown in figure 12. It can be seen that, the impact properties of the rotationally moulded product follow a similar trend like tensile properties. The increase in impact strength from 32 to 38 min of oven residence time can be attributed to the formation of small spherulites that grow sufficiently larger and get bonded with neighbouring particles. During this stage of polymer sintering, the pockets of air are entrapped in the melt because of the high viscosity of the polymer melt. With further increase in temperature the pressure inside such air pockets increases,

Table 4. Influence of oven residence time and degree of curing on tensile and flexural strength.

S. no.	Oven residence time in min	Degree of curing in °C-min	Curing time in sec above 200°C	Tensile strength in MPa	Flexural strength in MPa
1	32	1340.56	300	16	18.2
2	34	1600.85	350	16.2	18
3	36	1761.95	500	17.2	17.6
4	38	2088.51	550	17.4	17
5	40	2414.14	700	17.4	17.2
6	42	2494.90	800	16	16.7

thereby reducing their diameter. Such bubbles start escaping through the surface. As a result, the number of bubbles starts diminishing and can be seen in the form of increase in part density and improved impact strength.

With the above findings, it is possible to summarize the variation of mechanical properties with respect to the oven residence time as shown in figure 13. Based on the values of the mechanical properties a favourable processing window can be suggested that lies between 36 and 40 min (region between two vertical lines) where the highest

mechanical properties were obtained. Below and over these values, the quality of products obtained was inferior.

4.4 Verification experiments

Upon selecting the regime of favourable processing window (oven residence time between 36 and 40 min), confirmatory experiments were performed. Three replicates were obtained for each of three oven residence time. The results of the confirmatory experiments are shown in table 5. It could be seen that the values of tensile, impact and flexural remain to their highest values under the selected process conditions.

5. Conclusions

In this paper, the effect of oven residence time on the mechanical properties of rotationally moulded LLDPE products was investigated. Experiments were conducted on a laboratory scale rotational moulding machine by varying the oven residence timings from 32 to 44 min. The products were tested for tensile, flexural and impact strengths according to ASTM standards. It was observed that all the above properties showed an increased trend from 32 to 40 min. This can be attributed to the formation of a homogeneous melt due to escapement of entrapped air pockets with increase in temperature. One important observation was that the PIAT of 200°C was not only important factor, but also the time the polymer spends beyond this temperature is also crucial in governing the

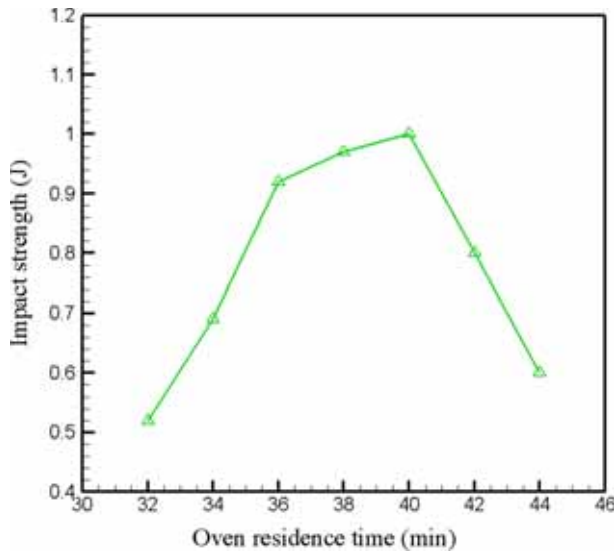


Figure 12. Variation of impact strength with respect to cycle time.

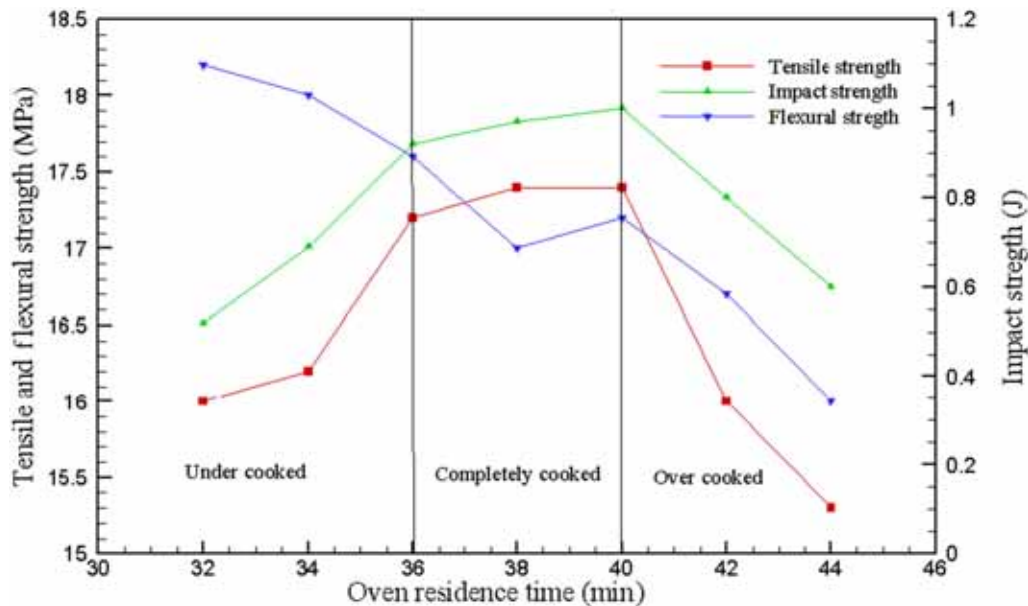


Figure 13. Processing windows for LLDPE product (thickness 3 mm) processed in an aluminium mould.

Table 5. Verification experiments.

Trial no	Oven residence time (min)	Tensile strength (MPa)	Average tensile strength (MPa)	Impact strength (J)	Average impact strength (J)	Flexural strength (MPa)	Average flexural strength (MPa)
1	36	17.4	17.4	0.92	0.94	17.2	17.1
2		17.4		0.94		16.9	
3		17.6		0.96		17.4	
4	38	17.6	17.6	0.94	0.96	17	16.9
5		17.6		1		15.5	
6		17.8		0.96		18.2	
7	40	17.6	17.4	1.1	1	17.2	17
8		17.4		0.92		17.2	
9		17.4		1		16.8	

mechanical properties. Simulation studies were conducted to analyze the different thermal transitions along with phase changes and the degree of curing of the polymers was assessed. This is correlated with the mechanical properties. It was also observed that the mechanical properties were reduced beyond 40 min of oven residence time, though theoretically high degree of curing was obtained. This can be attributed to the degradation of the polymer which was confirmed by conducting DSC studies. Thus, a regime of favourable processing window was obtained between 36 and 40 min where the maximum tensile strength of 17.4 MPa, flexural strength of 17.1 MPa and impact strength of 1 J was noticed.

It should be emphasized here that on an industrial scale, the rotational moulding machines take very less time to reach the set temperature (around 220°C) due to the presence of high capacity gas (or diesel) burners. As in our case an electrically heated oven was used, more time was needed for the oven to reach the preset temperature of 220°C. This can be regarded as one of the practical limitations of this study. The factors like rotational speed ratio, cooling rate also contribute to the above properties. With increase in thickness, the issues like warpage of the part need to be addressed separately. However, similar studies can be conducted on an industrial scale and correlated with simulation studies. The correlation of simulation and experimental studies provide new insight of process control that can be extended to polymers like Polypropylene and ABS having a narrow processing window but excellent mechanical properties.

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