Infrared assisted polymer forming

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ABSTRACT: In recent years a new technology has been studied for polymer forming. Plastic shaping was performed by means of the combination of IR heating and pellet softening in a semi-transparent mould, which allowed the radiation transmission. In the current work moulding tests were performed on ABS material (acrylonitrile-butadiene-styrene) by using a very low holding force (20 N). Several thin disks 20 mm in diameter were produced in different process conditions and subsequently characterized by dimensional analysis and mechanical tests. The pellet agglomeration was good as well as the aesthetic aspect. Mechanical performances were evaluated by plate bending test. A finite element (FE) model was defined to infer elastic modulus and yield stress. Finally, the best process conditions were identified to minimize the moulding time without affecting the moulded material properties.

Key words: Direct pellet forming, IR heating, Acrylonitrile-butadiene-styrene ABS, Plate bending tests

1 INTRODUCTION

Plastic components can be produced by different processes like injection moulding, extrusion and compression moulding. The most common is surely the first process, in which a melted polymer is forced to flow into a cavity of desired shape and then allowed to solidify under high holding pressure. The components fabricated by means of this process generally show high material and shape modifications due to many factors, such as orientation, degradation, thermal and flow stresses, crystallisation distribution and thermal shrinkage.
Many researches has been done to study the injection moulding process, evaluating for example the orientation in the components, the mechanical properties of adjacent flow weldlines and the stresses induced by the polymer flow and by the temperature change during the cooling stage. These stresses generally cause the warpage of the moulded part and affect its appearance and properties [1-2]. Moreover in the injection moulding process a great amount of energy and time is lost to initially melt and subsequently flow and cool the material [3]. These phenomena could be partially avoided if pellet agglomeration is obtained by direct moulding of heated pellets. In this case less energy is required for material heating, material degradation and orientation are reduced.
A first step in the direction of the direct pellet moulding was made by the authors, who proposed the use of a diode laser to agglomerate thermoplastic pellets [4-5]. In subsequent studies, plastic shaping was performed by means of the combination of IR heating and pellet softening in a semi-transparent open mould [6]. A simple exponential model was defined to predict the moulded sample thickness and a master curve was built for different thermoplastic materials.
Subsequently a closed-die direct moulding was performed to fabricate disks in ABS (acrylonitrile-butadiene-styrene) material [7]. The influence of the process parameters (IR power and interaction time) was discussed; a master curve was built and the model for the prediction of the moulded thickness was applied also to the closed-die configuration. The best fabrication condition was identified considering

only the aesthetic aspect.

In the present work a closed-die configuration was used to fabricated moulded disks in ABS. Dimensional and density measurements were performed. Moreover, plate bending tests were carried out to evaluate the mechanical performances of the moulded material in terms of elastic modulus and yield stress. A FE model was necessary to extract material properties from the experimental bending curves.

2 MATERIAL AND METHODS

2.1 Moulding

Moulding tests were performed on ABS pellets by means of the experimental apparatus shown in figure 1. An IR system with a 2 kW maximum power (LineIR 5194) was used for heating and a very low force was applied for pellet moulding (20 N) by means of calibrated weights external frame.

Table1. Moulding Parameters

	Moulding		Pre-heating			
	Power (W)	Time (s)	Power (W)	Time (s)	Average Thickness (mm)	Density (g/cm^3)
1	2000	40	1400	10	0.53	1.20
2	1800	50	1400	10	0.57	1.16
3	1600	60	1400	10	0.60	1.25
4	1400	80	1400	15	0.75	1.18
5	1000	330	1400	30	0.63	1.15
6	1800	45	1200	20	0.66	1.21
7	1800	40	1000	40	0.56	1.17
8	1800	35	1000	45	0.62	1.21

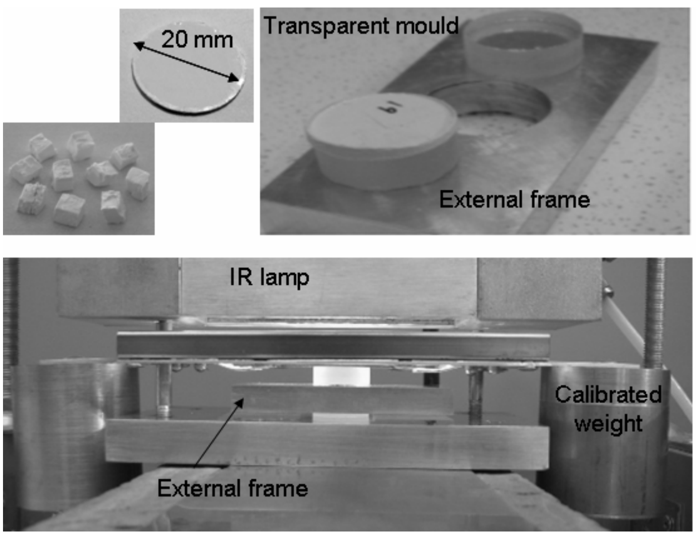

Fig. 1. Experimental apparatus for direct pellet moulding.

Cylindrical components (thin disks 20 mm in diameter) were obtained by using a transparent die consisting of three parts, two flat punches that can slide inside an external frame. The two punches were made of transparent glass, whereas the external frame was made of aluminium. During the moulding tests a single pellet layer was used. The material softening and moulding occurred during IR heating. The distance between the IR lamp and the pellet surface was fixed at 25 mm.

The material used in the experimentation was a commercial ABS (Dow MAGNUM R 213), available in the form of pellets for injection moulding. During the moulding tests, 12 pellets were placed on the surface of the lower transparent mould. A pre-heating was performed for a process time reduction and for better agglomeration. In the subsequent phase, the weight was applied on the pellet layer for all the radiation exposure time. When a good shape consolidation was achieved, the load was removed and the mould was left to cool to room temperature. After the disk extraction, the final thickness and the density were measured.

Table 1 reports the experimental conditions (lamp power and interaction time) for the pre-heating and the moulding phase. In the first tests (1-5) moulding parameters were varied at the fixed pre-heating power of 1400 W. The best combination in terms of low process time, good pellet agglomeration and good aesthetics was identified as moulding power of 1800 W and interaction time of 50 s (test n°2). Moving the process parameters around this optimum, it was changed the pre-heating time to further reduce the moulding process time without affecting pellet agglomeration and disk aesthetics. Therefore, in the last tests (6-8) the moulding power was fixed at 1800 W and the moulding time was reduced, by increasing the pre-heating time. Table 1 also shows the final thickness of the moulded disks together with the related densities.

2.2 Mechanical tests

The plate bending tests were carried out by means of a universal material testing machine (MTS Alliance RT/50). It was used a cylindrical punch 2 mm in diameter and a support with a coaxial hole 5 mm in diameter. The punch was made of tungsten carbide whereas the support was made of aluminium alloy. The test rate was 1 mm/min and the pre-load was 10 N.

Figure 2 shows a typical plate bending curve. After an initial linear elastic stage, a yielding point occurs. Thanks to the small size of the punch and the support coaxial hole, three tests were performed on each disk. Table 2 reports the average values of all the slopes and the yielding forces, which were extracted from the experimental curves.

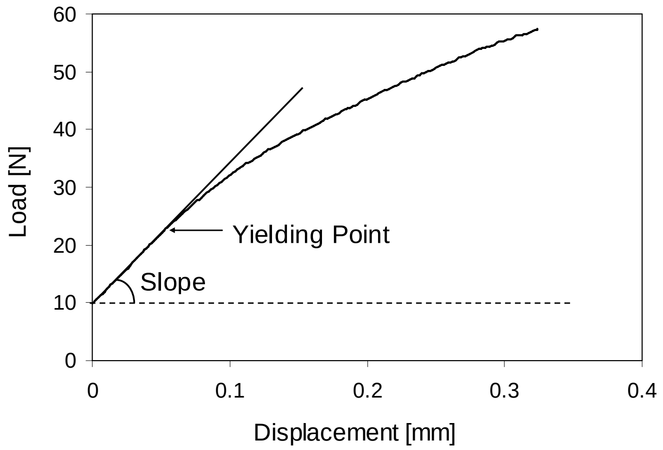

Fig. 2. Plate bending curve for the disk n°7 (moulding phase: 1800 W, 40 s; pre-heating: 1000 W, 40 s).

Table2. Data extracted from the experimental curve and numerical simulation

			Experimental		Numerical	
	Power (W)	Time (s)	Slope [N/mm]	F_{yield} [N]	E [MPa]	σ_{yield} [MPa]
1	2000	40	198.91	21.52	2100	45.66
2	1800	50	213.48	20.75	1834	38.03
3	1600	60	284.43	27.25	2127	45.31
4	1400	80	369.24	36.36	1547	39.54
5	1000	330	256.42	25.56	1690	38.60
6	1800	45	288.75	25.92	1663	35.55
7	1800	40	231.69	20.96	2075	39.95
8	1800	35	270.52	23.71	1860	36.96

3 NUMERICAL MODELLING

A 2D axis-symmetric FE model was built to infer elastic modulus and yield stress from experimental slope and yield force. The model was built in ANSYS Rel.9 by means of the parametric design language (APDL) to predict the effect of dimensional and material parameters on the test results. Figure 3 shows the mesh for a generic simulation, contact elements were inserted in the punch-disk interface as well as the disk-support interface.

For the plate bending simulation, a trial and error procedure was implemented. For each experimental bending curve, the measured disk thickness was used to built the mesh whereas the punch and support dimensions were constant. All the materials (ABS for the disk, aluminium alloy for the support and tungsten carbide for the punch) were considered linear elastic and homogenous. Nominal properties were considered for the tungsten carbide and the aluminium alloy, whereas the elastic modulus of the ABS was changed until the numerical slope became equal to the experimental one.

The FE model allowed also to extract a generalized law for the dependence of the test slope on the disk thickness. Figure 4 reports this dependence for different values of the elastic modulus. These curves can be normalised by means of the elastic modulus as figure 5 shows. The final curve can be fitted by means of a polynomial law, which can be used for a fast extraction of the elastic modulus from the experimental slope.

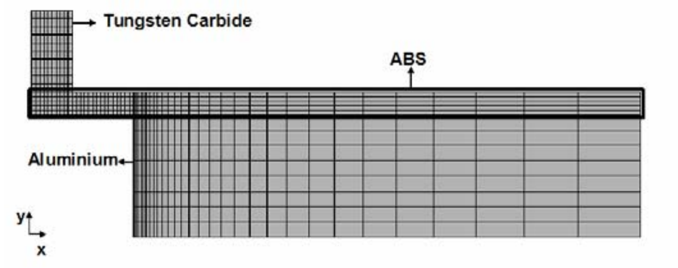

Fig. 3. 2D mesh for the simulation of the plate bending test.

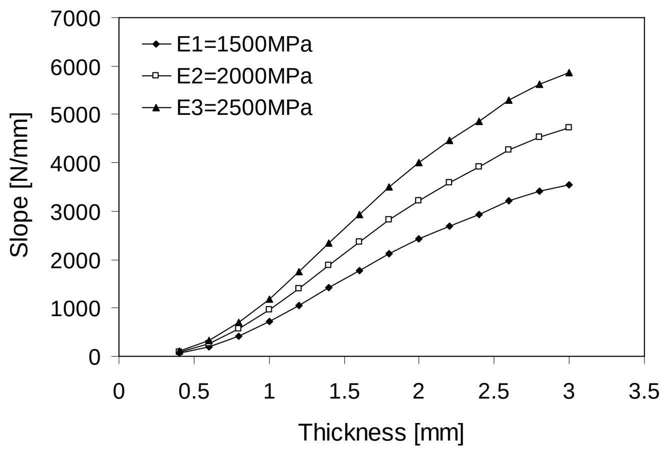

Fig. 4. Plate bending simulation: numerical slope as a function of the disk thickness for different elastic modulus.

In order to extract the yield stress, the same model of figure 3 was implemented with the real ABS modulus and the corresponding yield force was applied. After simulation, the average longitudinal stress in the lower disk surface was extracted as shown in figure 6.

The inferred elastic modulus and yield stress are summarised in Table 2 for each disk.

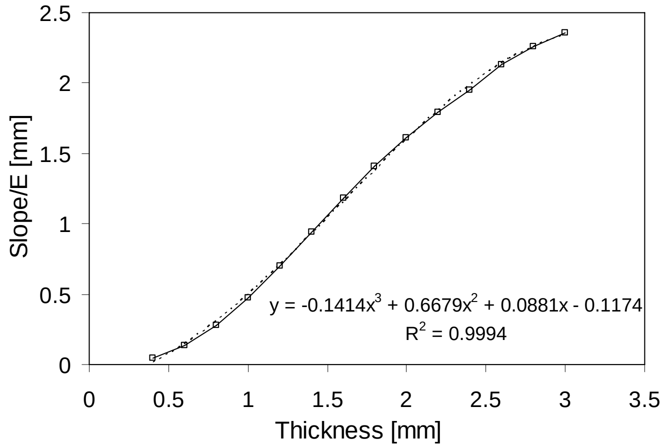

Fig. 5. Plate bending simulation: normalization of the numerical slope as a function of the disk thickness.

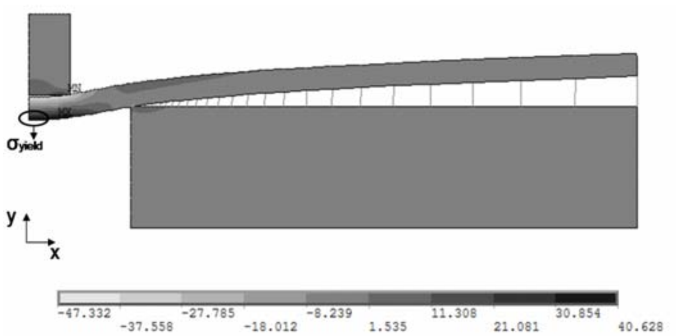

Fig. 6. Simulation of a plate bending test for the disk n°7 (moulding phase: 1800 W, 40 s; pre-heating: 1000 W, 40 s).

4 RESULTS AND DISCUSSION

Almost all the moulded disks presented a good agglomeration and aesthetics. At the highest value of 2000 W for the moulding power, the moulded surface started to burn.

From the moulding tests, an average thickness of 0.62 mm was obtained together with an average density of 1.19 g/cm^3, which is comparable to the density of an injection moulded part. However, mechanical properties significantly differ by varying the process parameters. An optimal combination of power and process time allows to increase the moulded material modulus and yield stress. By fixing the pre-heating time at 10 s, an optimum in the process was obtained at 1800 W. In order to reduce the moulding time, the pre-heating time has to be increased. In this case the optimum is obtained with a preheating time of 40 s and an equal moulding time.

5 CONCLUSIONS

Thermoplastic disks can be produced by direct pellet moulding, by using a very low pressure combined with an IR heating. A good pellet agglomeration and aesthetics were achieved and a density comparable to an injection moulded part was obtained.

Process time seems to be high, if compared to injection moulding times. For this reason, in this work, a pre-heating was performed for a process time reduction. In fact the pre-heating time can be covered by the moulding time of a previous part. Moreover, process time could be further reduced by automation or by enhancing the material absorption of the radiation. By using the same power and time for the pre-heating and the moulding phase, varying the distance between the IR lamp and the pellet surface, it is also possible to use the same IR source both to mould a disk and to pre-heat the pellets that will be successively shaped.

In the current work, for the first time, the disks fabricated by IR assisted forming were mechanically characterised. A plate bending tests was used, which allowed to perform several tests on the same disk and to define a generalised law for the elastic modulus extraction.

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