Residual Stress Analysis in Injection Moulded Polycarbonate Samples

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Abstract. The current paper presents results of residual stress measurements in injection moulded polycarbonate samples, which have been processed in various ways to introduce different residual stress states. The hole drilling as well as the ring-core method were used and methodological developments as compared to measurement procedures applied on metallic samples are outlined. In this context the time dependent viscoelastic behaviour of the investigated material as well as temperature fluctuations during testing are of high importance. It is demonstrated that manufacturing parameters, i.e. mould temperature and injection rate, have a significant impact on the resulting residual stress states. A frame made of aluminium was used to induce pronounced tensile residual stresses in the sample by preventing shrinkage. Holes of different diameters were drilled in order to get information at different depths from the surface.

Introduction

Injection moulding is a widely used manufacturing process for components made of plastics. The process comprises three stages: filling, packing and cooling. Each stage affects the materials properties of the moulded product and contributes to the formation of residual stresses. Many investigations deal with their analysis by testing and/or simulation [1]. As residual stresses can cause warpage and shrinkage, they are mostly undesired. However, it was also demonstrated that they can have positive effects on the materials properties. Compressive residual stresses improve the notched Izod impact strength [2] as well as slow down crack propagation [3]. Nevertheless, residual stresses are always superimposed to external stresses, and, thus, it is of crucial importance to predict them. Although simulation methods have been steadily improved, predictions have to be confirmed by measurements. The hole drilling method enables measuring depth gradients of plane stress states locally. Thereby, the hole drilling method can be used for samples with a minimum curvature of 3.5 times the diameter of the hole for an uni-axial stress state [4], while a minimal curvature of 6 times the diameter is recommended for multi-axial stress states [5]. However, plastics are challenging materials for mechanical stress measurement methods, as they are highly influenced by temperature fluctuations and behave like a visco-elastic material [6, 7]. In the current work it will be shown that injection rate and mould temperature significantly influence the absolute values of residual stresses in polycarbonate samples. Due to a hybrid structure made of polycarbonate and aluminium, which has been designed for the current work, it is demonstrated that the hole drilling method is appropriate to measure compressive as well as tensile residual stresses in the polycarbonate. By drilling holes with diameters of 2 mm and 4 mm and milling a circumferential slot with an inner diameter of 14 mm, it is revealed that the results are reproducible and eventually information about residual stresses is obtained at different depths following various treatments.

Materials and experimental set up

Four samples with the dimensions of 60 mm × 155 mm × 4 mm were prepared for the current work. All samples were injection moulded using Polycarbonate (Makrolon 2805). The injection moulding

parameters are given in Table 1. The material is characterized by a Young's modulus of about 2.7 GPa and a measured Poisson´s ratio of 0.4.

Table 1: Injection moulding parameters of the different samples

	Sample 1	Sample 2	Sample 3	Sample 4
Injection Rate (mm/s)	1000	100	100	100
Mould Temperature (°C)	30	80	80	80
Packing Pressure (MPa)	50	50	50	50
Melt Temperature (°C)	290	290	290	290
Additional Information			Annealed	With aluminium frame (Fig. 1)

Process parameters of sample 1 were employed to manufacture a sample showing high residual stresses. A high injection rate of about 1000 mm/s, which should promote high flow-induced residual stresses [1], and a low mould temperature of about 30°C were chosen. For the other samples, the mould temperature was increased to 80°C and the injection rate reduced to 100 mm/s. The third sample was annealed for 6 hours at 110°C after moulding in order to release residual stresses. As the thermal stresses were expected to be the main mechanism inducing residual stresses [1], compressive residual stresses were expected near the surface. In order to generate tensile residual stresses near the surface, the fourth sample was moulded in an aluminium frame, which prevents shrinkage of the polycarbonate in the longitudinal direction. Thus, tensile residual stresses in the longitudinal direction were expected at point A in Fig. 1. At the outer parts of the sample (Point B in Fig. 1) shrinkage in the transversal direction is also prevented, as the width of polycarbonate, i.e. the sample dimension in transversal direction, is bigger at the outer part than in the middle of the sample. Thus, tensile residual stresses in the transversal direction are expected at point B. Because of the equilibrium of residual stresses, compressive residual stresses are then expected in the transversal direction in the middle of the sample (Point A in Fig. 1).
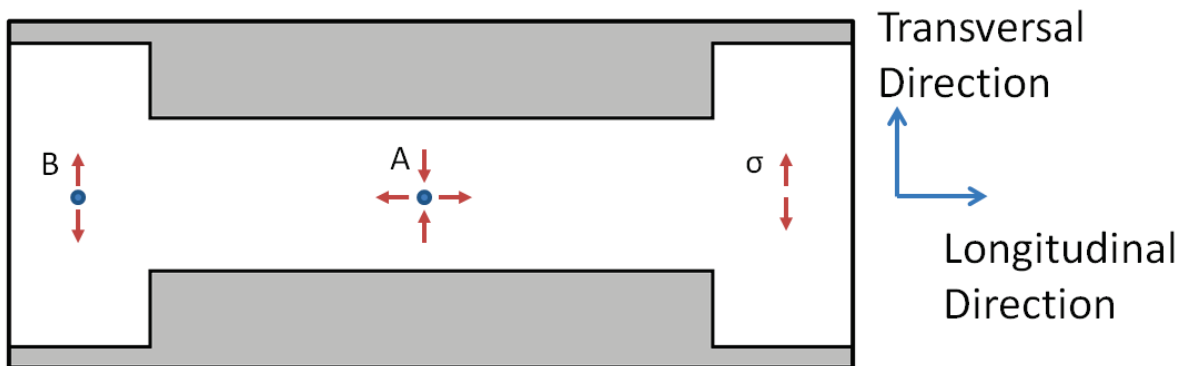

Figure 1: Polycarbonate sample (white) with an aluminium frame (grey). The thickness of the frame is 4 mm. The red arrows highlight the expected orientation of the residual stresses. See text for details.

In order to measure residual stresses, the hole drilling method was applied. Measurements were carried out at point A in Fig. 1, using the standard procedure [9], and following the recommendations in [6, 7, 8]. Calibration coefficients correlating residual stresses and released strains were calculated by Finite Element Analyses (FEA). The reader is referred to the aforementioned studies for details including guidelines detailing strain gauge installation and analysis of the time dependant measured strain signals. The signal is in fact strongly influenced by temperature fluctuations and the visco-elastic behaviour of the polycarbonate sample during and after drilling. In order to address these

issues the authors developed a procedure that minimizes effects. Findings will be reported elsewhere [6]. For the hole drilling method, two measurements were made for each sample: one with a 2 mm diameter blind hole at depth increments of 0.04 mm, and the second one with a 4 mm diameter blind hole at depth increments of about 0.08 mm. The ring-core method was also applied. The internal diameter of the circumferential slot was 14 mm and the external diameter was about 17 mm. The depth increments were 0.2 mm. Those three experiments were conducted complementary on each of the tested samples to gain information about residual stresses at different depths.

Experimental Results

The results of the residual stress measurements and the corresponding released strains are shown in Figs. 2 and 3. In Fig. 2 the results are arranged according to the measurement technique applied. The graphs a and b depict results obtained by the hole drilling method with a 2 mm diameter hole; the graphs c and d show respective data obtained by the hole drilling method with a 4 mm diameter hole; the graphs e and f finally depict results from the ring-core method. The curves in Fig. 2 are designated with the production parameters of the specimen (mould temperature and injection rate) or special treatments (annealed or with aluminium frame). For the purpose of clarity, the released strains are only highlighted by the maximum measured strain from the strain gauge rosette, and only the principal residual stresses are shown. For sample 4 both principal stresses are shown in red in Fig. 2. The samples 1, 2 and 3 almost show rotationally symmetric stress fields; therefore, only one principal stress is depicted in Fig. 2. The small difference between maximum and minimum residual stress is shown in Fig. 3. The maximum principal stress is exactly in the longitudinal direction (cf. Fig. 1). In Fig. 3 results are summarized differently. Graphs a and b highlight residual stress profiles of sample 4, which was moulded in an aluminium frame; graphs c and d depict data for the sample with a mould temperature of 30 °C; graphs e and f show residual stresses of the annealed sample.

Fig. 2b reveals that all samples have a compressive residual stress maximum at a depth of approximately 0.3 mm. This can also be found in Fig. 2d. As expected, the annealed sample shows the lowest amount of residual stress. If not annealed the sample shows a maximum compressive residual stress of about -3.3 MPa. Reducing the mould temperature to 30 °C and increasing the injection rate to 1000 mm/s results in a 40% higher compressive stress of about -4.6 MPa. The sample with the aluminium frame shows the highest absolute value of residual stresses. It reaches compressive stresses of about – 6 MPa and an average tensile stress of about 3 MPa, which are in the transversal and longitudinal direction, respectively (cf. Fig. 1). Similar residual stress profiles with constant tensile stress in the middle of the sample are reported in literature [1]. The result of the ring-core method shown in Fig. 2f seems to be less accurate. This can be attributed to the geometry of the model used in FEA to calculate the calibration coefficients. The sample was actually modelled as a 60 mm diameter disc. Modelling based on a 200 mm diameter disc provides slightly differing coefficients and, thus, affects results especially at the depth of 3.4 mm, where the result was so much diverging that it could not be shown. However, this difference is not sufficient for explaining the divergence at the depth of 2.4 mm, where the absolute value of the residual stress is strongly increasing. As this increase is also seen for the stress free sample, this result doesn´t seem to be reliable. Concerning sample 4, its aluminium frame wasn´t modelled in the simulation. This shouldn´t influence the results obtained by the hole drilling method significantly, as the hole diameter is small, but surely influences the ring-core measurement having a much larger measuring diameter. Consequently, in Fig. 2f the ring-core measurement was only evaluated up to a depth of 2 mm, as from here on errors occurred due to new residual stress equilibrium and the weak adhesion between polycarbonate and aluminium. Still, Fig. 3 shows a good agreement between the measurements made employing the hole drilling method with a 2 mm diameter and 4 mm diameter independent of the condition of the tested sample.
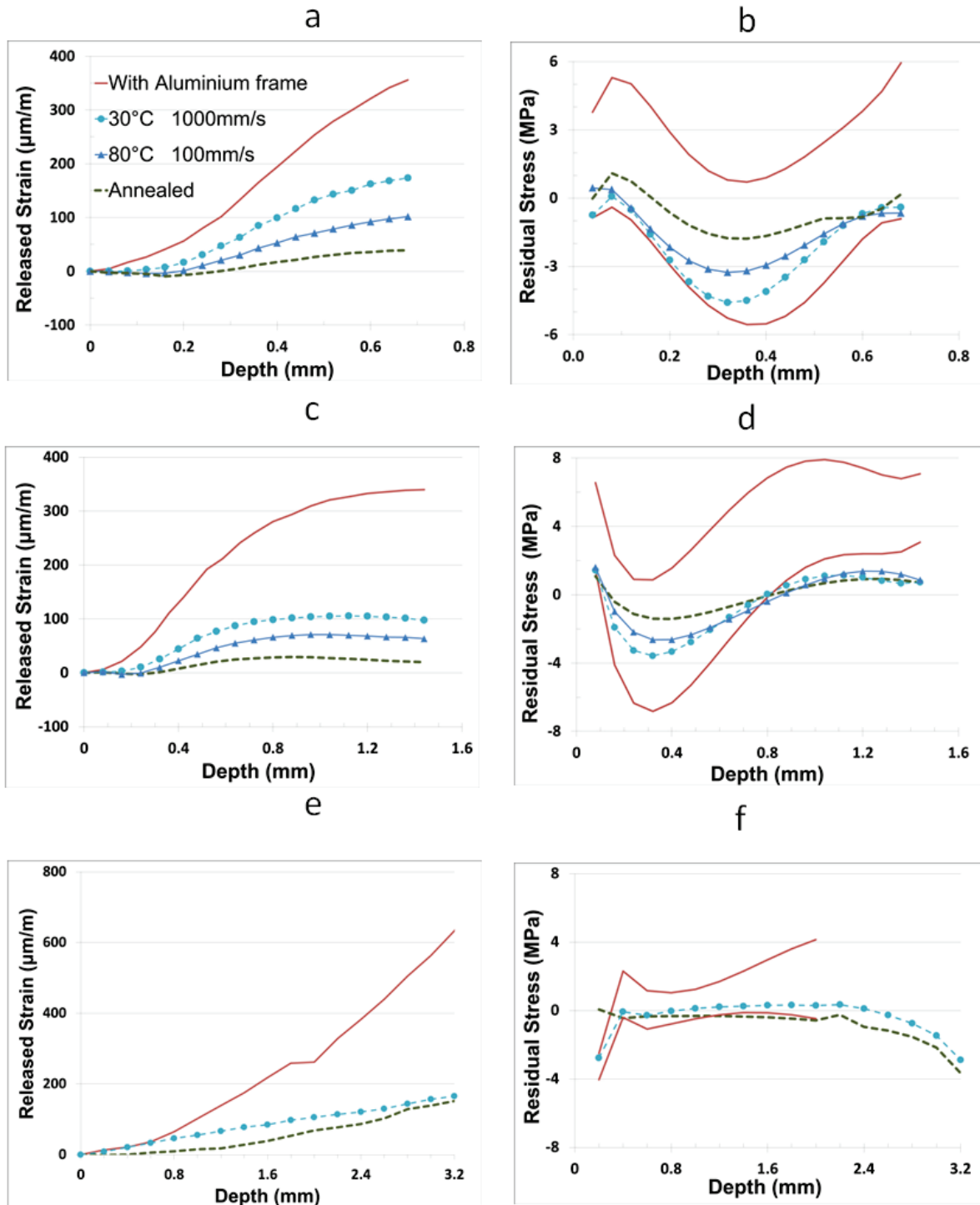
Figure 2: Released strain and measured residual stress applying the hole drilling method with a 2 mm hole (a and b), a 4 mm hole (c and d) and applying the ring-core method (e and f). Due to rotationally symmetric stresses, only one principal stress value is plotted for samples manufactured without the aluminium frame
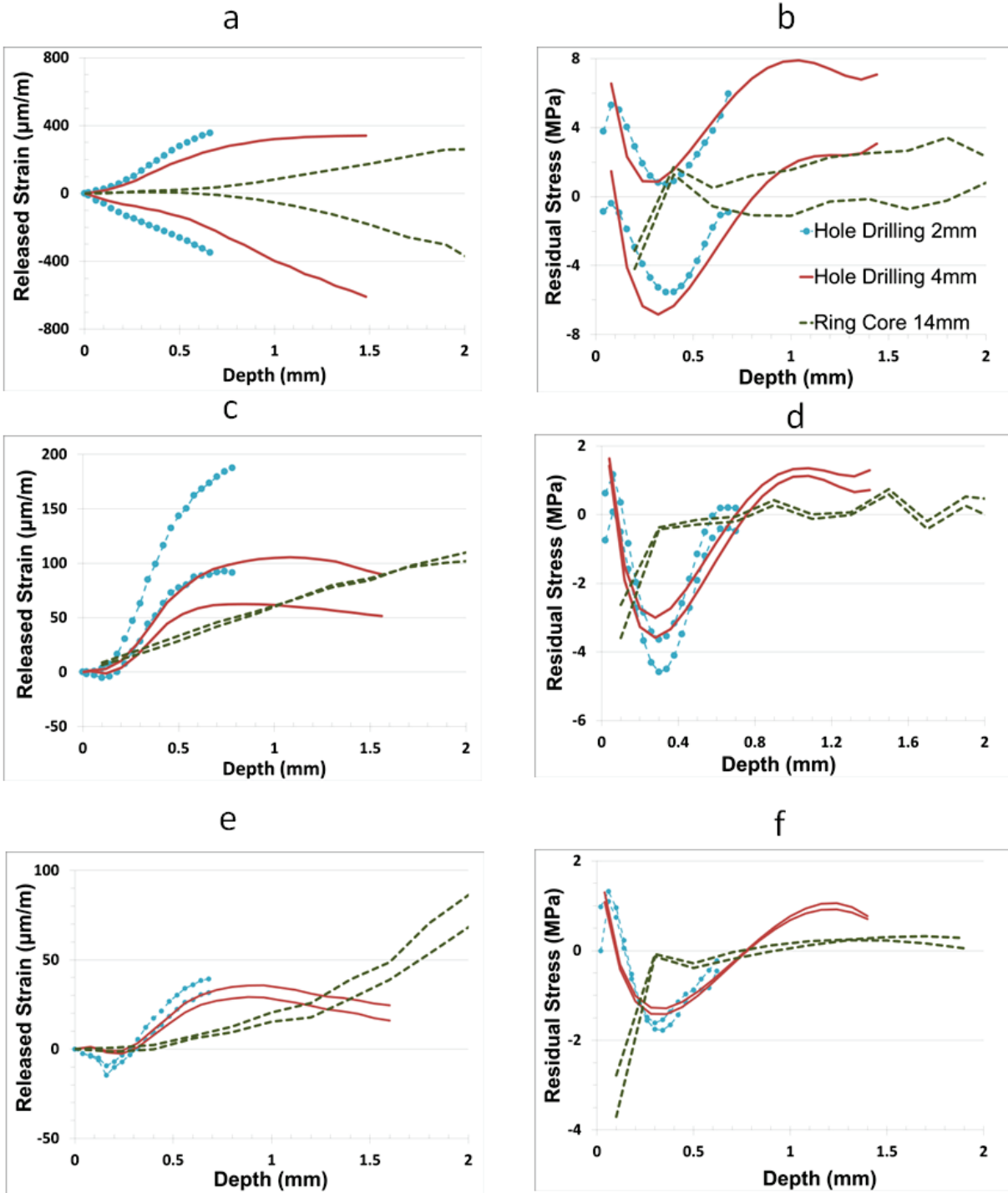
Figure 3: Measured maximum and minimum released strain and principal residual stress in polycarbonate samples: samples moulded into an aluminium frame (a and b), with a mould temperature of 30°C (c and d) and post-moulding annealed (e and f)

Conclusion

Residual stress profiles were characterized on polycarbonate by applying the hole drilling and the ring-core methods. The measurements employing the hole drilling method revealed the expected trend of the residual stress profiles. Varying the injection moulding parameters, different maximum

amounts of compressive residual stresses were introduced and measured near the surface. It was also possible to set and determine tensile residual stresses within the whole depth of a sample by moulding into an aluminium frame. The results of the hole drilling method could be obtained with two different hole diameters. The results using the ring-core method were less satisfactory and may be strongly affected by the geometry of the sample, including the aluminium frame. In summary, the results presented prove that reliable residual stress analyses in plastics can be carried out provided that appropriate measurement parameters are applied. Thereby, temperature fluctuations and the visco-elastic material behaviour have to be considered adequately.

Acknowledgements

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