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Mechanical properties of gas-assisted injection moulded PS, PP and Nylon parts

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Abstract

PS, PP and Nylon plate parts designed with gas channels having five different types of cross-section but with same section area were gas-assisted injection moulded (GAIM). Mechanical properties of GAIM parts were investigated via tensile and bending tests. Effects of part thickness, shape and associated dimensions of gas channels on tensile and bending properties of GAIM parts were examined. It was found that maximum tensile load and ultimate tensile stress show only slight influence from gas channel design and part thickness except Nylon parts which exhibit significant dependence on part thickness due to degree of crystallinity. Gas channel design, introducing additional moment of inertia, results in part structural reinforcement. Part stiffness and maximum bending load basically increases linearly with the moment of inertia and the section modulus of the plate, respectively. Gas channel design attached with top rib (shapes D and E) show the best effect of structural reinforcement. For brittle PS parts, plates with semicircular gas channel (shape A) exhibit maximum flexural strength. PS parts with rectangular gas channel design (shape B) can absorb more bending energy than the other designs. The present study provides part designers with a design guideline for choosing the most effective gas channel design to achieve a specific objective of part structural performance.

Keywords: Gas-assisted injection; Mechanical properties; Gas channel

1. Introduction

Gas-assisted injection moulding (GAIM) is one of the most important innovative moulding processes recently developed [1–4]. In this process, the mould cavity is partially filled with polymer melt followed by the injection of inert gas into the core of the polymer melt. A schematic diagram of the gas-assisted injection moulding process is shown in Fig. 1. This process can substantially reduce operating expenses through reductions in material cost, clamp tonnage and [1–13] in cycle time for thick parts. In addition, the tough issues encountered in conventional injection moulding (CIM) such as sink marks, residual stresses and warpage may also be greatly reduced, especially for the large parts whose quality and rigidity are the main concerns when employing GAIM. It also allows more design freedom in using structural ribs and bosses which would introduce sink marks and other associated issues on surface appearance when moulded by CIM. Although gas-assisted injection provides many advantages when compared with conventional injection moulding, it also introduces new processing parameters and makes the application more critical. One of the key factors is the design of gas channels which guide the gas flow to the desired locations. If the layout of gas channels and their corresponding shapes and dimensions in cross-sections are not properly designed, catastrophe often occurs in the moulded parts. In addition to the design parameters introduced by gas channels, other processing parameters such as the numbers as well as the locations of gas injection points, amount of polymer melt injection, delay time, injected gas pressure and holding time for gas injection, etc., are also important in obtaining good moulded parts. Generally speaking, only when the design and processing parameters are well understood, can the gas-assisted injection moulding process obtain its advantage. Due to the complexity of gas channel design and processing control, computer simulation [3,7,8] is expected to become an

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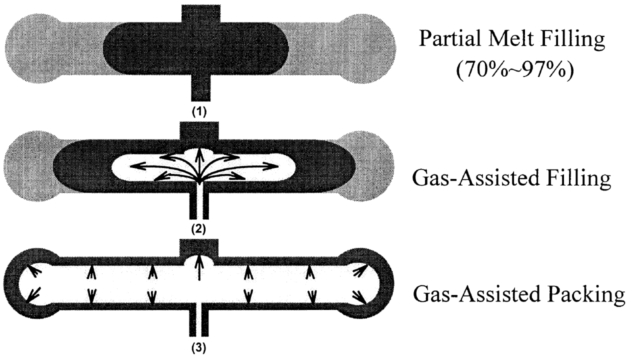

Fig. 1. Schematic diagrams of the gas-assisted injection moulding process.

important and a required tool to assist in part design, mould design and process evaluation in the coming age. Fundamental studies concerning the effect of gas channel design on gas penetration [5–8], moulding window [9] as well as part properties [10–16] are also required to build quantitative design/moulding guidelines which are very helpful for the application of GAIM.

In conventional injection moulding, ribs are used in plastics parts to improve rigidity and structural integrity. However, the design limit for the heights and thickness of ribs has been very strict due to the possible introduction of sink marks on the back wall of ribs. Gas-assisted injection moulding may allow the rib thickness to be designed up to over three times the nominal wall thickness. For example, one can change the rib design moulded by CIM to GAIM by widening the rib bottom and connecting it to one gas channel or allowing it to be part of the gas channel. Or, one can use gas channel design to perform structural reinforcement, meanwhile minimizing the conventional rib design. From the part designer's viewpoint, it is very important to have a design/moulding guideline concerning the capability of structural reinforcement of gas channels, particularly the dependence of mechanical properties on the shape and the associated dimensions of gas channels, as well as the hollowed core geometry in a quantitative manner. Although previous studies [1–4, 10–14] mentioned that mechanical strengths of GAIM parts can be improved as compared with CIM parts; nevertheless, there are not enough experimental data for quantitative conclusion until now. Baxi [12] reported that the gas-assisted injection moulded parts have a higher stiffness to weight ratio. A more recent study by Grelle et al. [15], who evaluated bending performance for four types of rib structures (tall rib, short rib, square rib and double rib) manufactured by three different moulding processes (solid injection, foam injection, gas injection), found that gas-assisted injection moulding provided a slight advantage over the others in three of four rib structures when comparing part strength to weight ratio. As far as peak load leading to failure is concerned, the tall rib shows higher values than those of the other ribs. Grelle and associates' work, although providing a first step toward the quantitative guideline for GAIM part structural design, it is far more complete in the correlation of other bending properties such as stiffness, flexural strength, absorbed energy, etc., to gas channel design. In our recent investigation series, mechanical properties including tensile properties, bending performance, impact strength for different thick GAIM parts designed with various gas-channel sections of different dimensions were investigated using PS, PP, PC, ABS and Nylon (with/without fibres). In the present paper, plate parts designed with gas channels having five different types of cross-section but with the same channel section area were moulded using three different materials including PS, PP and Nylon (without fibre) in order to evaluate the tensile and bending properties of GAIM parts. Tensile and bending tests similar to the methods of the American Society for Testing and Materials (ASTM) [17] were conducted. Effects of geometrical factors introduced by part thickness, various gas channel designs and the associated hollowed core geometry on the tensile and bending properties were analyzed and correlated. From the measured data, a guideline for determining the most effective gas channel design can be established so

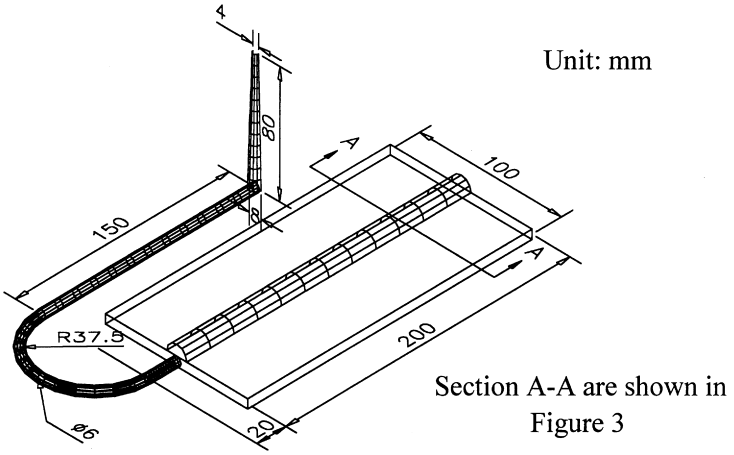

Fig. 2. Mould geometry for the thin plate cavity with a gas channel.

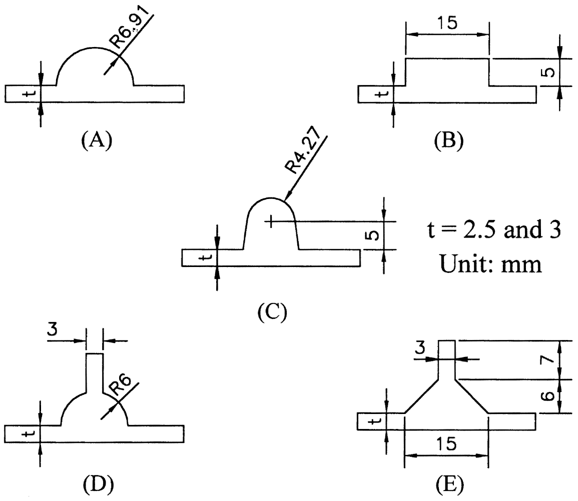

Fig. 3. Gas channels of five different types of cross-section geometry.

that part designers are able to achieve a specific design objective in part structural performance.

2. Experimental section

A 75 ton Battenfield 750/750 co-injections moulding machine and an Airmold gas injection system with the capacity for five-stage pressure profile control were used for the experiments. A plate mould allowing 2.5 and 3 mm thickness as depicted in Fig. 2 was designed with gas channels having five different types of cross-section (Fig. 3). The area under channel cross-sections were all the same. Three different materials including PS (amorphous), PP (semi-crystalline) and Nylon (semi-crystalline) were used to mould the plate parts. Preliminary studies found that moulding conditions were more critical to the gas penetration length and the moulding window. For mechanical property investigation, gas penetration must be properly controlled. As a result, suitable moulding conditions are limited. Test parts were all moulded within the range of mouldable conditions [9]. Ten samples moulded under the same moulding conditions were used for each type of test. The average values from these ten tests were used for analysis and correlation. Tensile and bending tests were performed.

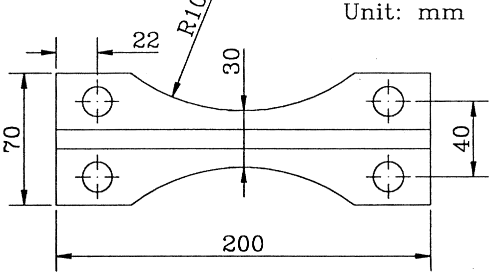

Fig. 4. Shape and dimensions of tensile test specimen.

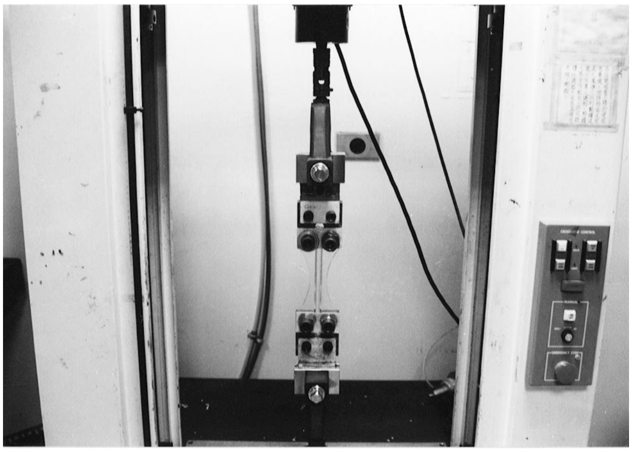

Fig. 5. Experimental apparatus and set-up of tensile test.

2.1. Tensile tests

Owing to the gas channel design, the standard ASTM sample for tensile test cannot be applied directly. After several trials, specimens with a modified shape similar to D2289 of the ASTM testing methods, as shown in Fig. 4, were prepared for the tensile test. The tensile tests were conducted on a C-MTS machine, whose full load was 5000 kgf. Self-designed grips were employed for holding the wide, thin plate-shape specimen designed with the gas channel to obtain good alignment. The displacement speed employed is 1 mm min^{-1} for PS and 10 mm min^{-1} for PP and Nylon. Experimental apparatus and set-up are shown in Fig. 5. The specimen broke around the centre of the specimen during the test. From the tensile test, the maximum tensile load of the specimen, $P_{t_{max}}$ (N), and the ultimate tensile stress of specimen, $\sigma_{t_{max}}$ (N m^{-2}), were obtained. A typical case of tensile load (P_t) vs. deflection (δ_t) for Nylon plate parts (3 mm and 2.5 mm thick) with gas channel of shape B is shown in Fig. 6.

2.2. Bending tests

The bending test is the most popular test for plastic parts, representing overall mechanical properties or structural performance. Bending tests have several advantages over tensile tests. The specimen for flexural test is comparatively easy to prepare without further shaping. Specimen alignment is also easier in bending tests. Moreover, at small strains, the actual deformations are sufficiently large to be measured accurately. Bending tests were also conducted on the C-MTS machine. A special specimen-holding fixture was designed and mounted on 1/8th inch (3.2 mm) round bar stock spaced 140 mm apart and it was allowed rotate freely when applying the bending load. A three-point loading system was used for this test, and the strain rate was 0.01 mm mm^{-1} min^{-1} for PS and 0.1 mm mm^{-1} min^{-1} for PP and Nylon. A schematic diagram of specimen arrangement for bending tests is shown in Fig. 7. A typical case of

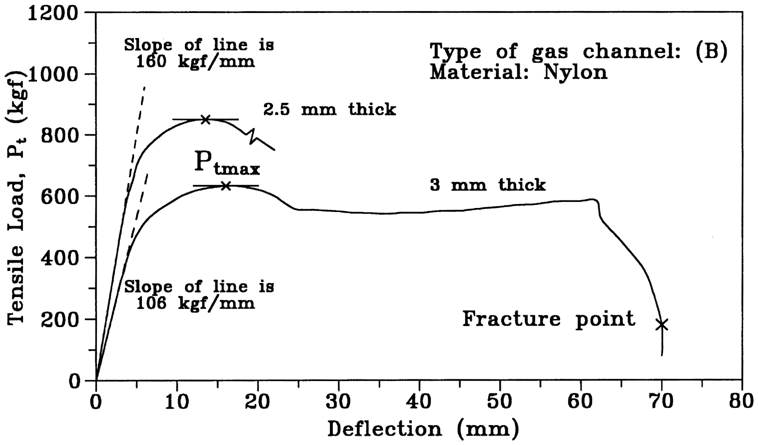

Fig. 6. Typical curve of tensile load vs deflection (Nylon part with shape B gas channel design).

bending load vs deflection for a 3-mm thick PS GAIM part with 6.91 mm radius in semicircular (Shape A) gas channel (designated as R6.91T3) is shown in Fig. 8. From the experimental data describing the variation of load vs deflection, the following parameters can be obtained or calculated:

E_b (N m^{-2})	Young's modulus.
P_b (N)	bending load of plate.
$P_{b_{max}}$ (N)	maximum bending load of plate. Definition of $P_{b_{max}}$ for PP and Nylon are different from that of PS as shown in Fig. 9 because PP and Nylon will not break under current loading condition.
σ (N m^{-2})	bending stress of plate.
σ_f (N m^{-2})	flexural strength.
δ_b (m)	deflection at the midpoint of the plate in vertical direction.
δ_{max} (m)	maximum deflection at the midpoint of the plate in vertical direction.
K (N m^{-1})	stiffness K is defined as the force required to produce a unit deflection, that is, $K = P_b/\delta_b$. Definitions of K for PS, PP and Nylon are shown in Fig. 9, respectively.
A (m^2)	cross-sectional area.
W (kg)	part weight.
$P_{b_{max}}/A$ (N m^{-2})	maximum bending load/cross-sectional area.
Absorbed energy (N m)	total absorbed energy of plate during bending, which is equal to the areas under curve $P_b - \delta_b$ up to break.
Absorbed energy/W (N m kg^{-1})	total absorbed bending energy of plate/part weight.
M (N m)	bending moment at the middle point of the plate along span direction.
M_{max} (N m)	maximum bending moment at the middle point of the plate along span direction.
I (m^4)	moment of inertia, defined from part cross-section with respect to the neutral axis.
C (m)	largest distance from the neutral axis to the free surface of gas channel, as shown in Fig. 7.
L (m)	length of span, as shown in Fig. 7.

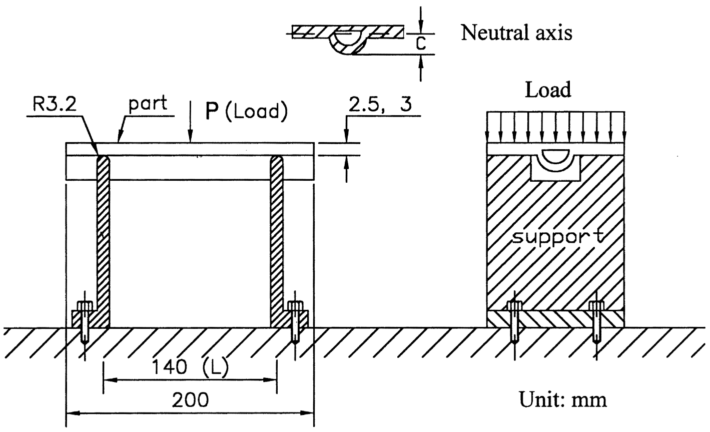

Fig. 7. Schematic diagram of bending test for GAIM plates.

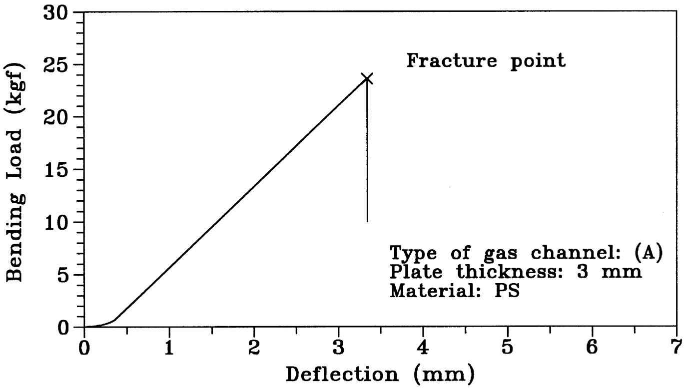

Fig. 8. Typical curve of bending load vs deflection (3 mm PS plate with shape A gas channel).

For small loading, a linear relationship exists between P_b and δ_b. According to the mechanics of materials [18], P_b and δ_b are related by:

$$\delta_b = \frac{P_b \cdot L^3}{48 \cdot E_b \cdot I} \tag{1}$$

For fixed values of both Young's modulus (E_b) and span distance (L), one can rearrange Eq. (1) to obtain P_b/δ_b (i.e., K). K is found to be proportional to I, that is:

$$K \propto I \tag{2}$$

The larger the moment of inertia, I, the greater the stiffness, K. Moreover, the maximum fibre stress is related to the load and the sample dimensions by the following relationship:

$$\sigma = \frac{M \cdot C}{I} = \frac{1/4 P_b \cdot L \cdot C}{I} \tag{3}$$

Flexural strength is equal to the maximum stress in the exterior surface of the gas channel at the moment of breakage. This value can be obtained from the stress Eq. (3) by letting the load value P equal to load at the moment of break. The result is:

$$\sigma_f = \frac{M_{max} \cdot C}{I} = \frac{1/4 P_{b_{max}} \cdot L \cdot C}{I} = \frac{1/4 P_{b_{max}} \cdot L}{I/C} \tag{4}$$

where I/C is the section modulus of the cross-sectional area. For fixed values of both L and σ_f, one will find that $P_{b_{max}}$ is proportional to section modulus (I/C), that is:

$$P_{b_{max}} \propto I/C \tag{5}$$

Eq. (2) and Eq. (5) will be used for later discussions. In principle, both $P_{b_{max}}$ and σ_f can be defined only for PS parts which were bent to break during the test. However, for the purpose of comparison, $P_{b_{max}}$ was also defined for PP and Nylon parts, as shown in Fig. 9.

3. Results and discussions

3.1. Tensile performance

For the purpose of convenient discussion, the five different types of gas channels, as shown in Fig. 3, are represented

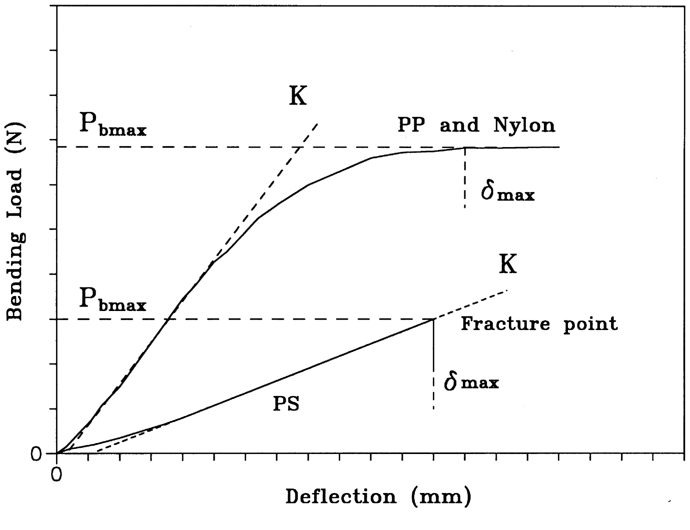

Fig. 9. Bending load vs deflection for PS, PP and Nylon GAIM parts. Stiffness K and maximum bending load $P_{b_{max}}$ are also defined.

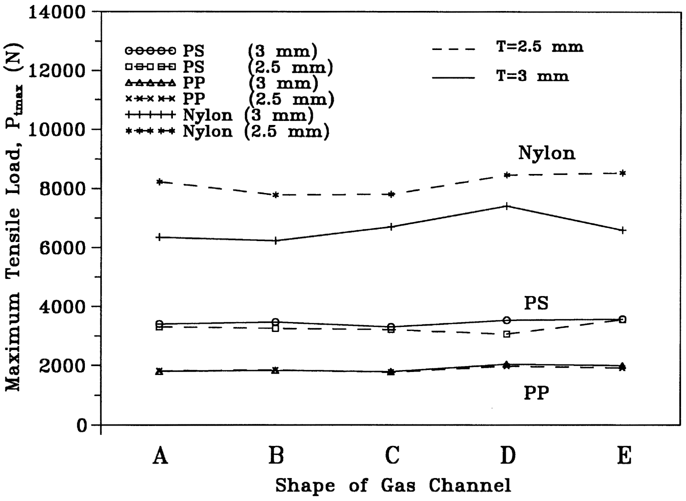

Fig. 10. Maximum tensile load for 2.5 and 3 mm GAIM plates designed with five different gas channels.

by the symbols (A), (B), (C), (D), (E), respectively. Graphical displays of the maximum tensile load and ultimate tensile stress for plates (of 2.5 and 3 mm thickness) designed with these five different gas channel designs can be found in Figs. 10 and 11, respectively. Upon examining these data, it is found that because of the approximately same cross-sectional area, all parts of the same materials and the same thickness have very similar values of both maximum tensile load and ultimate tensile stress. All deviations from the average value show approx. less than 10% for these five different gas channel designs. Generally speaking, it is evident that various gas channel geometries exert less significant influence on part tensile properties once gas channel design provides approximately the same part cross-sectional area, even though they may have a little difference in hollowed core geometry. In addition, from these figures, it is interesting to find that 2.5-mm thick PS plates show a slightly lower maximum tensile load than 3 mm plates. Similar situations occur in PP plates. However, 2.5 mm Nylon plates give approximately 10–15% higher values of $P_{t_{\max}}$ than those of 3 mm plates. Since the part cross-sectional area of the 3 mm plate is larger than that of the 2.5 mm plate, it is expected that the ultimate tensile stresses ($P_{t_{\max}}/A$) for 2.5-mm thick plates will be slightly greater than those of 3 mm plates. This situation is found in PS and PP plates. The former (2.5 mm plate) shows approx. 0–10% higher values over the latter (3 mm plate). For Nylon, the differences run up to approx. 30–40%. This indicates that $P_{t_{\max}}$ and ultimate tensile stress in Nylon plates are sensitive to the plate thickness. The reasons can be attributed to the degree of crystallinity in Nylon. Fig. 12*a* and 12*b* are X-ray diffraction measurements for both 2.5 and 3 mm Nylon plates at locations at a distance from and at the gas channel, respectively. 2.5 mm parts exhibit a higher degree of crystallinity than that of 3 mm parts at locations at a distance from the gas channel, but both show an almost equal degree

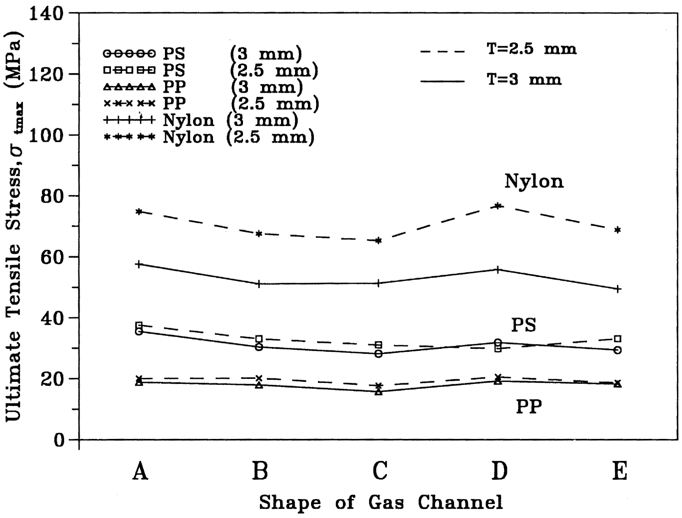

Fig. 11. Ultimate tensile stress for 2.5 and 3 mm GAIM plates designed with five different gas channels.

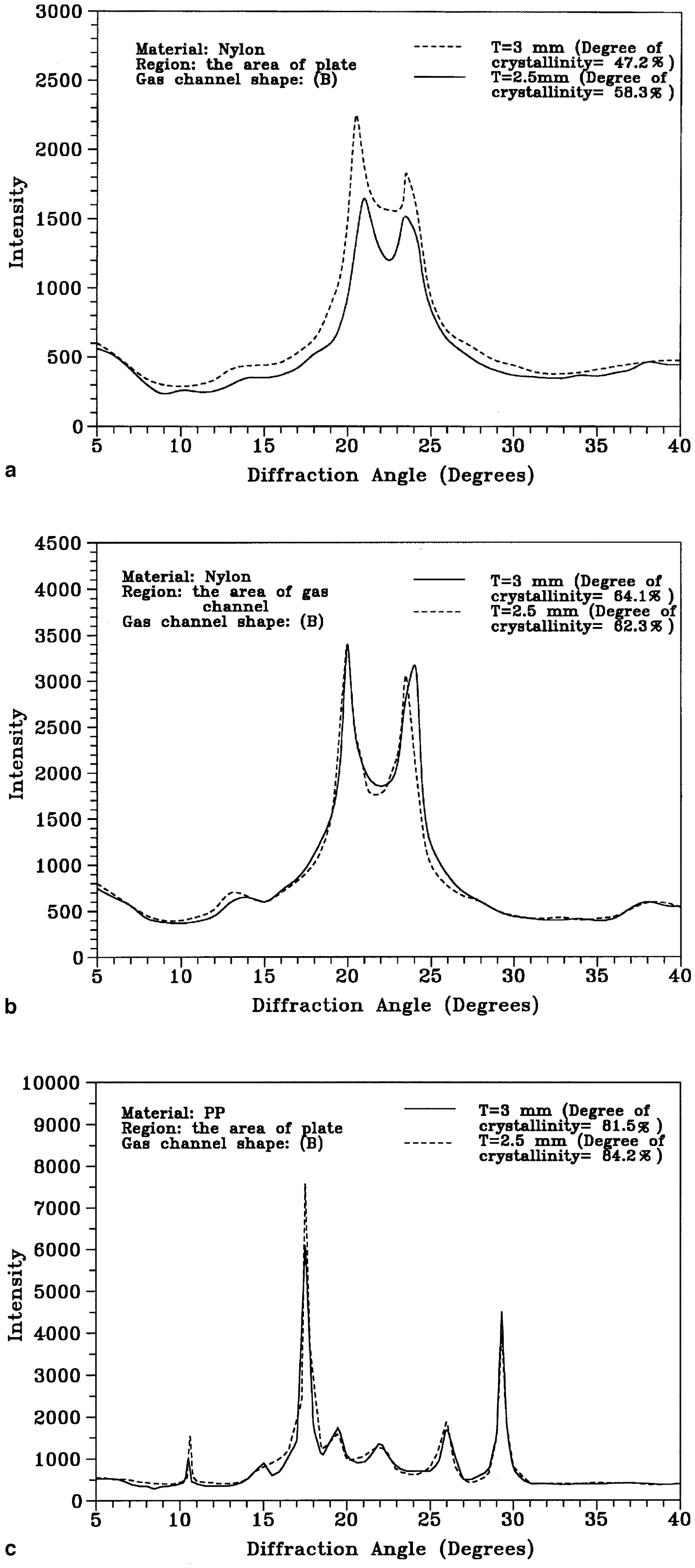

Fig. 12. (a) X-ray diffraction pattern for 2.5 and 3 mm Nylon GAIM plates at a distance from the gas channel. Degrees of crystallinity are also evaluated. (b) X-ray diffraction pattern for 2.5 and 3 mm Nylon GAIM plates at the gas channel. Degrees of crystallinity are also evaluated. (c) X-ray diffraction pattern for 2.5 and 3 mm PP GAIM plates at a distance from the gas channel. Degrees of crystallinity are also evaluated. (d) X-ray diffraction pattern for 2.5 and 3 mm PP GAIM plates at the gas channel. Degrees of crystallinity are also evaluated.

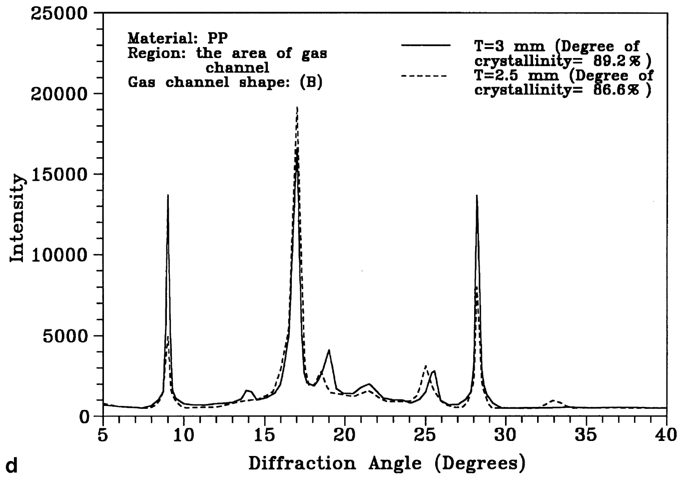

Fig. 12 (*continued*).

of crystallinity on positions at the gas channel. In PP materials, the degree of crytallinity is neither sensitive to part thickness nor location, as evidenced by Fig. 12*c* and 12*d*.

3.2. Bending performance

Fig. 13 shows the maximum bending load for both 2.5 and 3 mm plates designed with five different types of gas channels and moulded with PS, PP and Nylon. It can be noted that for PS and PP parts, part thickness and channel section shape do not exert a strong influence on the maximum bending load. However, in Nylon parts, plate thickness does affect the maximum bending load significantly. Again, this may be attribute to the dependence of the degree of crystallinity in Nylon parts on part thickness. Gas channel geometry also exerts a more distinguishable effect on the maximum bending load in Nylon parts (in the order: E $>$ D $\approx$ C $>$ A $>$ B). Generally, C, D and E gas channels give approx. 30–50% higher bending loads than those of channels A and B. The stiffness vs moment of inertia for both 3-mm and 2.5-mm thicknesses are shown in Figs 14 and 15, respectively. It is quite clear that stiffness shows a strong dependence on the moment of inertia which is determined by the gas channel shape, associated geometry and the corresponding hollowed core geometry. As a result, both moment of inertia and stiffness are in a sequence of E $>$ D $>$ C $>$ A $>$ B. Part thickness could also affect the moment of inertia but less significantly. From these two figures, it was found that the bending stiffness is approximately proportional to the moment of inertia. There is also a roughly linear relationship between the maximum bending load and the section modulus for PS parts, as shown in Fig. 16. These two results are consistent with Eq. (2) and Eq. (5), respectively. From the experimental tests, it is quite evident that gas channel types D and E have a greater capacity for structural reinforcement as regards both maximum bending load and bending stiffness. However, for PS parts

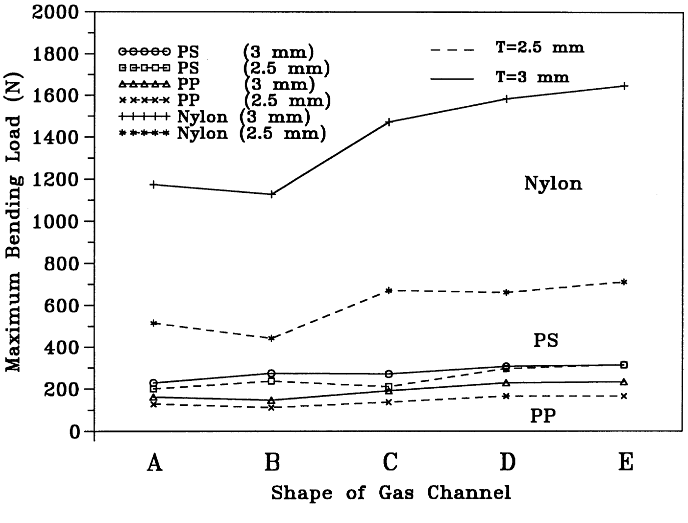

Fig. 13. Maximum bending load for PS, PP and Nylon plates.

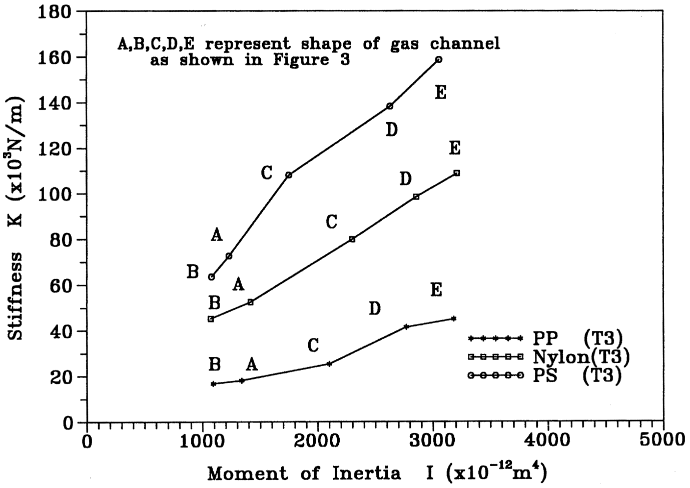

Fig. 14. Stiffness vs moment of inertia for 3 mm PS, PP and Nylon GAIM parts.

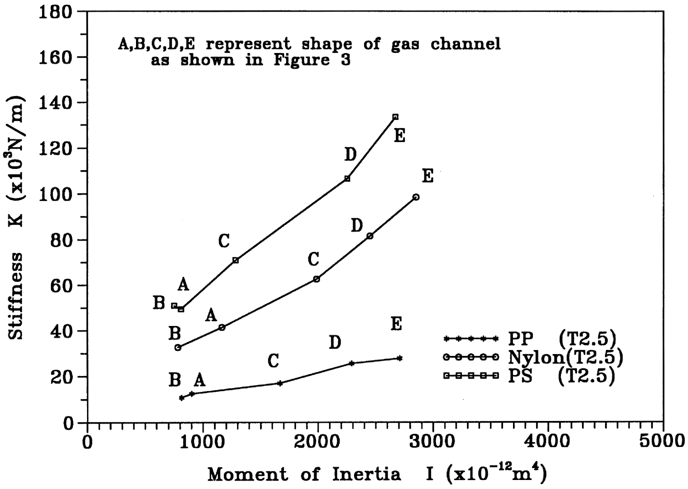

Fig. 15. Stiffness vs moment of inertia for 2.5 mm PS, PP and Nylon GAIM parts.

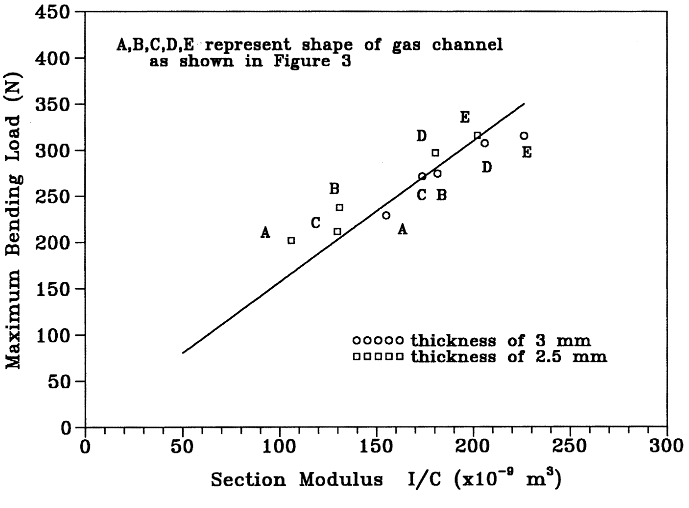

Fig. 16. Maximum bending load vs section modulus for PS GAIM parts.

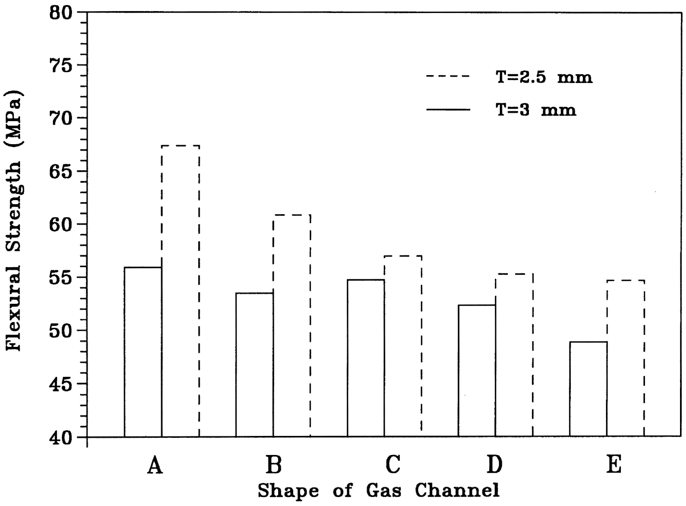

Fig. 17. Flexural strength for PS plates designed with five different types of gas channels.

which are basically brittle materials, these two gas channel designs are poor in bending flexural strength. The flexural strength of channel types D and E are approx. 5–24% lower than those of the others. The design of gas channel with semicircular cross-section (shape A) shows the highest flexural strength (Fig. 17). As far as absorbed bending energy and absorbed bending energy to weight ratio up to failure are concerned, a rectangular gas channel (shape B) provides an advantage of approx. 20–50% higher values than those of the other designs (Fig. 18).

4. Conclusions

Effects of geometrical factors introduced by part thickness and various gas channel designs on the tensile and bending properties of gas-assisted injection moulded PS, PP and Nylon parts were investigated via tensile and bending tests. Based on the measured results, the following conclusions can be made.

1. Maximum tensile load and ultimate tensile stress are only slightly influenced by gas channel design. All the deviations from the average value are less than 10% for the five different gas channel designs. Part thickness affects the maximum tensile load and ultimate tensile stress strongly in Nylon parts but less significantly in PS and PP parts. On average, 2.5-mm thick plates provide a slight advantage of 0–10% higher values in ultimate tensile stress than those of 3 mm plates for PS and PP. For Nylon parts, this advantage could be as great as 30–40%.
2. It was found that owing to the geometrical considerations of channel cross-section, as well as associated size and distribution of the hollowed core, gas channel design shapes D and E introduce higher values of moment of inertia and section modulus resulting in higher maximum

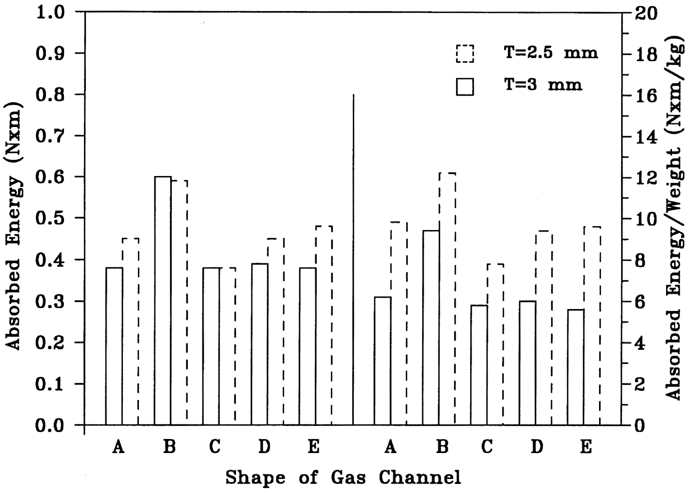

Fig. 18. Absorbed bending energy and absorbed bending energy/weight for PS plates.

bending load and higher bending stiffness. Both channel designs also provide the best enhancement effect in structure performance for all PS, PP and Nylon parts. However, brittle PS parts with semicircular gas channel, A, can be designed with maximum flexural strength. Rectangular gas channel design, B, in PS parts can absorb more energy than the other designs.

3. Experimental data indicate that part stiffness basically increases linearly with the moment of inertia of the plate. The gas channel will reinforce part structural performance by increasing the moment of inertia, the amount of which is determined by the shape and the dimension of channel section, as well as the hollowed core geometry. There is also a linear relationship between the maximum bending load and the section modulus for PS parts.

Acknowledgements

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