Proc. Estonian Acad. Sci. Engin., 1996, 2, 1, 72–88
https://doi.org/10.3176/eng.1996.1.08

STRENGTH AND DURABILITY STUDIES OF POLYPROPYLENE HINGES

Andres KRUMME and Anti VIIKNA

Tallinna Tehnikaülikooli polümeermaterjalide instituut (Department of Polymeric Materials, Tallinn Technical University), Ehitajate tee 5, EE-0026 Tallinn, Eesti (Estonia)

Received 4 March 1996, accepted 3 April 1996

Abstract. This paper focuses on the influence of different polypropylene (PP) brands and hinge geometry on hinge strength and durability for all bending angles allowed by the closure limit. Hinges of different PP grades, including homopolymer, copolymer with polyethylene and elastomeric compound were compared. Tensile, tear, and fatigue tests and their combinations were used to explain the hinge behaviour in relation to the hinge radius and thickness. PP homopolymers and copolymers guarantee the hinges a longer bending life. Increased hinge thickness leads to a higher hinge tensile strength, but the calculation of the tensile strength per hinge area showed that lower thickness hinges are stronger. The "ends geometry" of a hinge was not found to be the most important factor of its tear resistance.

Key words: hinge, hinge geometry, polypropylene, bending, tensile strength, tear, fatigue.

1. INTRODUCTION

Common long lifetime hinges consist of separate components, assembled after manufacturing. Living hinges, on the other hand, are moulded into a plastic item during the forming process. In this paper, the term *living hinge* means that two parts of a unit are connected by a thin web of material. No other mechanism is required, and the thin web forms a hinge as an integral part of a construction. One of the oldest uses of the living hinge is the book cover. Most modern uses are in plastic lidded containers, and wherever flexible bending connections are needed.

The main advantage of a living hinge is its low cost. Other advantages include high precision (injection moulded), smooth movement without lubrication, and a lower production cost than for an assembled hinge. However, the mould cost may be higher because larger moulds are required, and only a limited number of materials can be used.

Although living hinges are widely used, little has been published about their design, processing and suitable materials.

A typical hinge configuration is shown in Fig. 1.

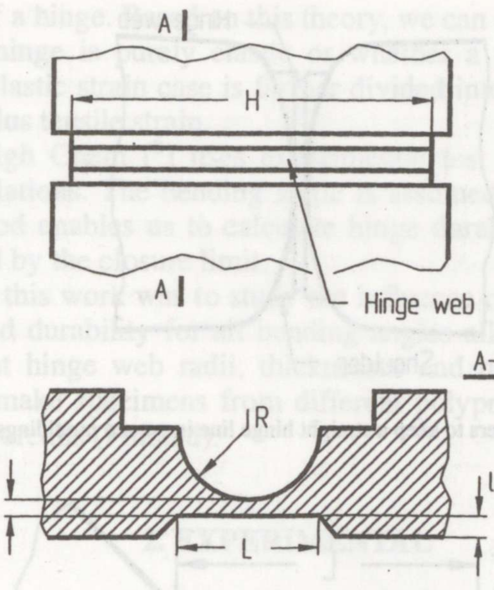

Fig. 1. Typical hinge configuration.

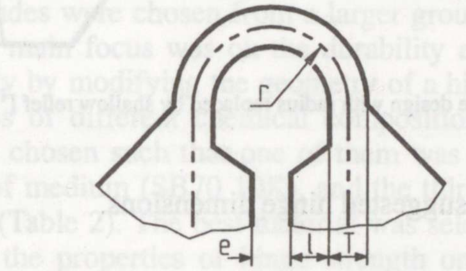

Fig. 2. Hinge closure limit and clearance [1].

Hinge web is formed by radius *R* on the one side of the hinge and by a shallow relief *L*, also called the hinge land length, on the other one. *T* is the thinnest part of the hinge between the radius and the relief. The depth of the relief is the hinge closure limit *l*, which determines the hinge clearance in a closed state (Fig. 2) [1].

Hinge width *H* (Fig. 1) depends on the geometry of the moulded details. If the hinge is long, it should be divided into several shorter hinges to avoid material flow along the hinge, which would cause a decrease in hinge strength [2]. Hinge line must be designed as a very slight curvature to introduce buckling action. If the edge of the moulding is curved, shoulders must be provided to preserve a straight hinge line (Fig. 3) [3].

For higher tear resistance, a radius at the ends of the hinge line can be used (Fig. 3). Radii are also added to the interface between the hinge and the part walls.

In summary, only two main hinge geometry types are suggested:

1. The hinge web is formed by the radius on the one side of the hinge and a shallow relief on the other one.
2. A shallow relief on both sides of the hinge web (Fig. 4) [1].

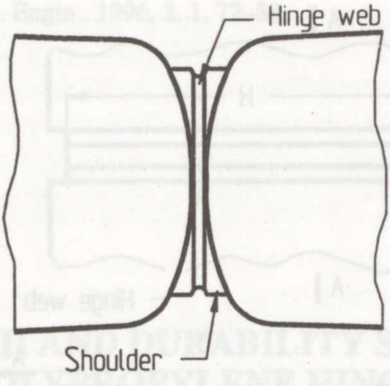

Fig. 3. Shoulders to keep a straight hinge line in curved mouldings [3].

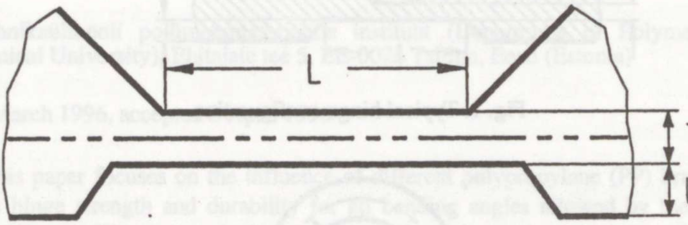

Fig. 4. Hinge design with radius replaced by shallow relief [1].

Table 1 reviews the suggested hinge dimensions.

Table 1

Suggested hinge dimensions [2–6]

Source	Hinge thickness *T*, mm	Hinge land length *L*, mm	Hinge radius *R*, mm
Fisher Price	0.45	2.5	1.5
Designers Guide	0.2–0.5	1.5–2.3	>0.8
Shell	0.2–0.4	1.5	0.75
Himont	0.2–0.4	1.5	0.8
Phillips	0.3–0.5 (0.8)	0.8–1.5	0.4–0.75
Fina Oil	0.2–0.3 (0.5)	0.75–1.5	0.75
Eastman	0.25–0.4	0.8–1.5	0.4
Propathene	0.2–0.6 (1.0)	1.5	0.75–1.0 (1.5)
Neste	0.15–0.8 (1.0)	1.5	0.75–1.5
Hoechst old	0.25–0.8	1.5	0.75–1.0
Hoechst new	0.3–0.8	1.0–6.0	–

Additional information about the calculations of hinge strength can be found in [1], where the basic theory of elasticity is used to calculate the bending life of a hinge. Based on this theory, we can establish whether the strain in the hinge is purely elastic or whether a plastic strain is also present. The plastic strain case is further divided into pure bending strain and bending plus tensile strain.

Hoechst High Chem [6] uses experimental test results in the hinge strength calculations. The bending angle is assumed to be 180° [1]. The Hoechst method enables us to calculate hinge durability for all bending angles allowed by the closure limit.

The aim of this work was to study the influence of hinge geometry on its strength and durability for all bending angles allowed by the closure limit. Different hinge web radii, thicknesses and hinge end geometries were used to make specimens from different polypropylene (PP) grades produced by Borealis (Finland).

2. EXPERIMENTAL

2.1. Materials

Three PP grades were chosen from a larger group of materials studied earlier [7]. The main focus was on the durability and improvement of a hinge, preferably by modifying the geometry of a hinge. For this purpose, the three grades of different chemical composition, tensile and fatigue resistance were chosen such that one of them was of the highest (VB80 33C), another of medium (SB70 10K), and the third of poor quality (DE 2561) material (Table 2). The best material was selected to determine the dependence of the properties of hinge strength on the hinge geometry. Lower-quality materials enabled us to estimate the hinge durability, as dependent on its geometrical design.

Table 2

Selected polypropylene materials

Grade	Material type	Melt flow rate, g/10 min*	Tensile strength, MPa**
VB80 33C	Homopolymer	8.0	35.0
SB70 10K	Block copolymer with polyethylene	7.0	27.0
DE 2561	Compound, elastomer	6.0	19.0

---

* According to ISO 1133.

** According to ISO 527.

2.2. Test specimens

A special mould was made to produce the hinge test specimen. It had a changeable hinge insert (nine different geometries) and two changeable gates: a film gate and a point gate. The mould consisted of a moving and a fixed part; the fixed part was flat, the moving one contained a mould cavity. The dimensions of the mould were selected to ensure testing and comparison of different hinge specimen geometries.

The test specimen consisted of two plates connected by a hinge web. By the plates, the specimen was clamped in different testing apparatuses. Specimen dimensions are shown in Fig. 5 and the geometry types of different testing purposes in Table 3.

In specimen design, most of the available types of hinges were taken into account (Table 1) to find the best possible variety in terms of strength and durability properties.

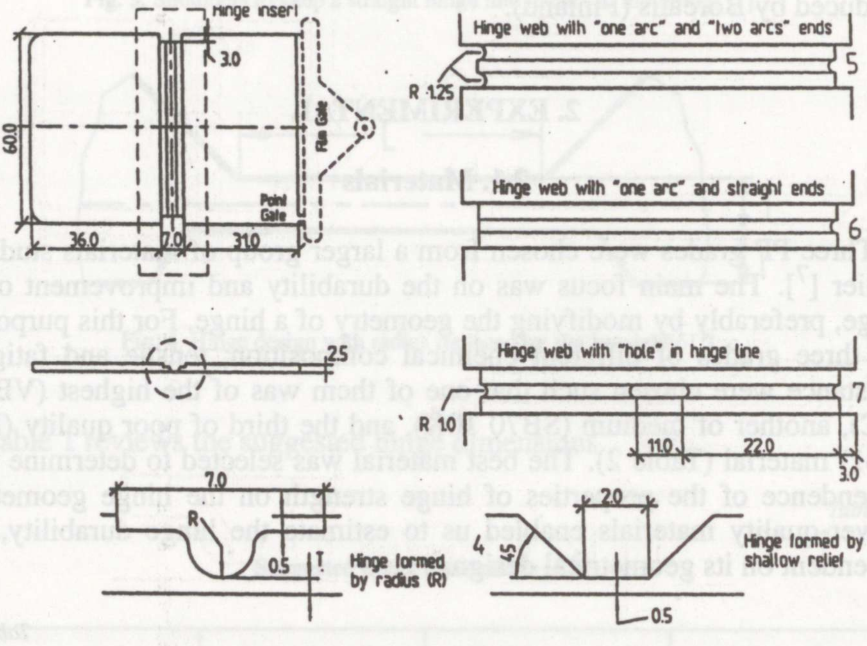

Fig. 5. Test specimen dimensions (numbering as in Table 3).

Table 3

Test specimen description

No	*T*, mm	*R*, mm	Available special geometry	Testing purpose
1	0.2	0.75	Straight ends	Radius and thickness vs. strength and fatigue
2	0.5	0.75	Straight ends	Radius and thickness vs. strength and fatigue
3	0.5	1.0	Straight ends	Radius and thickness vs. strength and fatigue
4	0.5	1.0	Straight ends, hinge formed by shallow relief	Method of hinge forming vs. strength and fatigue
5	0.5	1.0	"One arc" + "two arcs"	"Ends geometry" vs. strength and fatigue
6	0.5	1.0	"One arc" + straight end	"Ends geometry" vs. strength and fatigue
7	0.5	1.0	"One arc" at both ends, hole in hinge line	Material flow through the hinge line with hole
8	0.8	1.0	Straight ends	Radius and thickness vs. strength and fatigue
9	0.8	1.5	Straight ends	Radius and thickness vs. strength and fatigue
10	1.0	1.5	Straight ends	Radius and thickness vs. strength and fatigue

2.3. Moulding procedure

Test specimens were moulded using the Krauss Maffei injection moulding machine KM 90/340B with 900 KN clamping force. The basic moulding conditions were: mould temperature – 50 °C, melt temperature – 240 °C and injection speed – 54 + 1 mm/s. 20–30 specimens were collected, weighed, marked and kept under standard conditions (25 °C, 50% humidity) for a minimum of 24 h before testing.

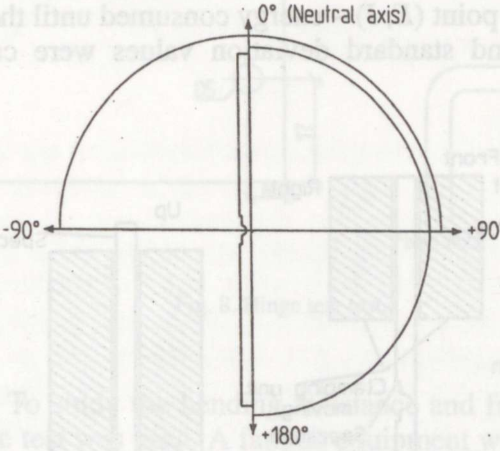

Fig. 6. Bending angles of a hinge.

2.4. Specimen preparation for testing

Before mechanical testing, hinge specimens were bent manually for the following purposes:

1. As the bending resistance of virgin hinges is too high for the fatigue equipment to start the testing, for the hinges thicker than 0.2 mm, one initial bend was made manually before clamping the specimens in the bending equipment. Bending angle was ±90° or +180° to −90° from the neutral axis (Fig. 6).
2. To compare mechanical properties of the bent and unbent hinges, 100 initial bends were made before testing of the tensile or tear strength of the hinge. Bending angle was ±90° from neutral axis (Fig. 6).

2.5. Test procedures

Tensile test. Instron tensile testing apparatus (model 4502) was used; a 5 or 10 KN load cell and a clamping unit were installed and calibrated. Upward test direction and 50 mm/min crosshead speed were used. A specimen was fixed by the clamping units (Fig. 7). Four unbent and four initial bent specimens were used for one testing series if no fatiguing was made before the tensile test. One hundred initial bends with ±90° bending angle were made manually. When the fatigue equipment was used before the tensile test, one, three or four specimens of one series were tested. The results of the tensile test were recorded until up to break point and the data were recorded by the tensile testing apparatus:

- Load at maximum load (Lo, KN) – maximum load registered during the tensile test.
- Load/with at maximum load (Lo/W, N/mm) – maximum load per hinge web length registered during the tensile test.
- Displacement at maximum load (DIS, mm) – elongation of the hinge area at maximum load.
- Energy to break point (*E*, J) – energy consumed until the breakage.

The average and standard deviation values were calculated for all series.

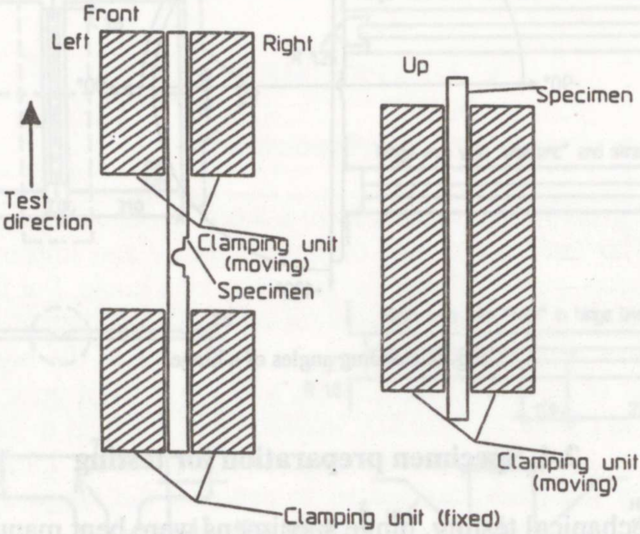

Fig. 7. Test specimen clamping in a tensile test apparatus.

Tear test. A tear test was performed to study the strength of hinge web ends. The Instron tensile test apparatus was adapted for this purpose. Clamping units were supplemented with hooks, fitting the perforation made into a test specimen (Fig. 8). This method concentrates the tensile stress on the end area of the hinge web. 5 or 10 KN load cell was installed and calibrated together with a clamping unit and a hook. An upward test direction and 50 mm/min crosshead speed were used. For each series, eight specimens were perforated, half of them were bent under ±90° manually for one hundred times. As a result of different geometry of the end of the hinge web, the specimen was cut into two equal pieces diagonally to the hinge web. Both sides were perforated and tested separately. The following data were collected by the tensile test machine:

- Load at maximum load, KN – maximum load registered during the tear test.
- Energy to break point (*E*, J).

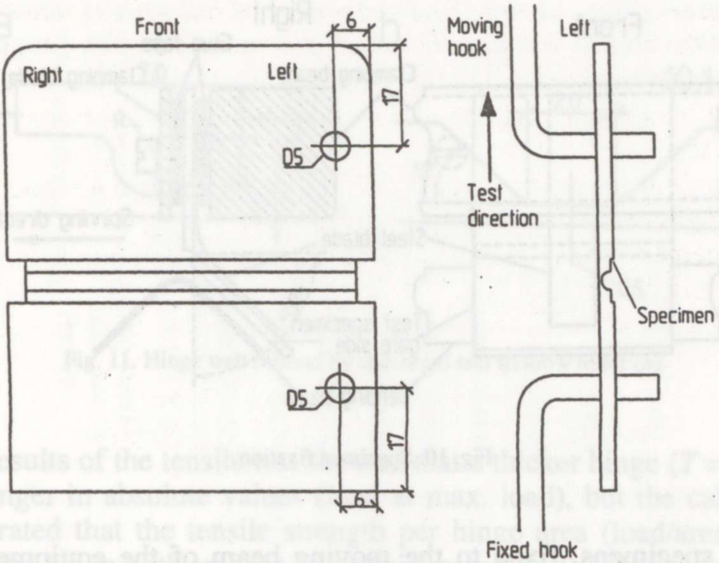

Fig. 8. Hinge tear test.

Fatigue test. To study the bending resistance and fatigue process of a hinge, the fatigue test was used. A fatigue equipment was built. A rotating system with an electric motor facilitated bending of 48 specimens simultaneously (Fig. 9). Bending occurred when rotating specimens had contact with a bending beam (Fig. 10). Bending angle of ±90° (two-directional rotation) or +90° (one-directional rotation) was available. The equipment incorporated a counter to record bending cycles.

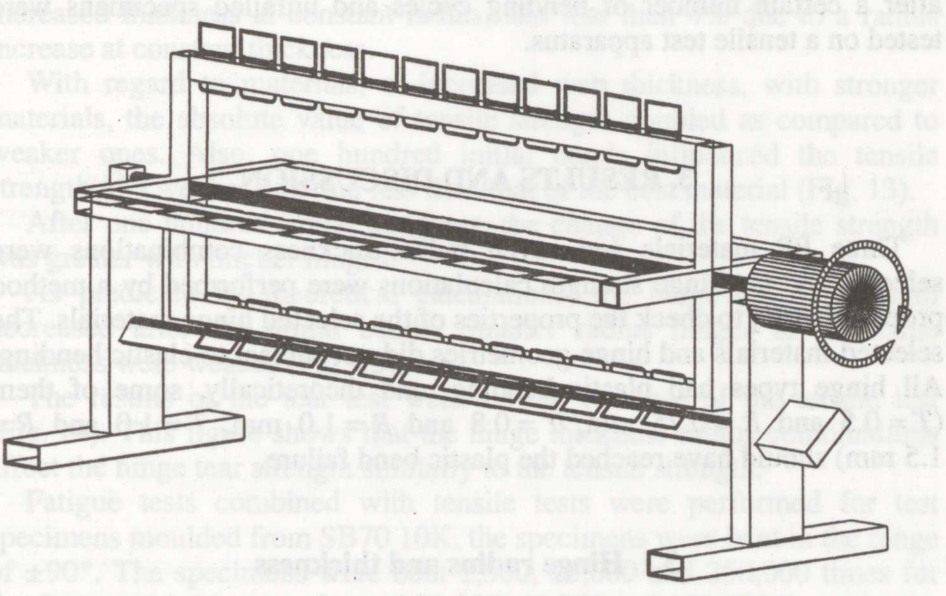

Fig. 9. The fatigue equipment.

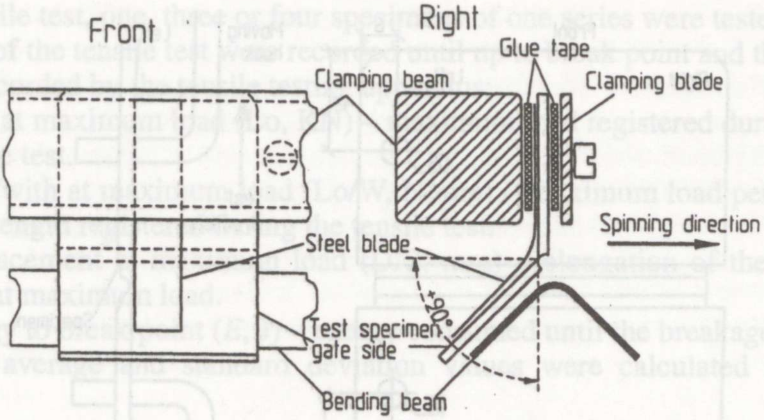

Fig. 10. Specimen fixation.

Three specimens, fixed to the moving beam of the equipment, were selected for one series. With the bending angle of the hinge ±90°, a steel blade spring was installed to return it to the neutral position after the bend (Fig. 10). Then the equipment was activated by one- or two-directional rotation. Two-directional rotation means that the spinning direction of the motor was reversed after one full revolution. One-directional rotation allowed us to make +90° bend and a two-directional ±90° bend. The speed of a one-directional rotation bending cycle was one bend per s and that of the two-directional rotation bending cycle was one bend per 4 s. In general, test specimens were bent until failure. The number of bending cycles was registered right after the hinge line breakage. When the fatigue test was combined with a tensile test, a series of specimens were collected after a certain number of bending cycles and unfailed specimens were tested on a tensile test apparatus.

3. RESULTS AND DISCUSSION

Three PP materials and seven radius-thickness combinations were selected and the hinge strength calculations were performed by a method proposed in [1] to check the properties of the selected hinge materials. The selected materials and hinge geometries did not subject to elastic bending. All hinge types had plastic bending, and theoretically, some of them ($T = 0.5$ and $R = 0.75$ mm, $T = 0.8$ and $R = 1.0$ mm, $T = 1.0$ and $R = 1.5$ mm) should have reached the plastic bend failure.

3.1. Hinge radius and thickness

Six hinge inserts with a radius and one with a shallow relief forming the hinge web were used (Fig. 11).

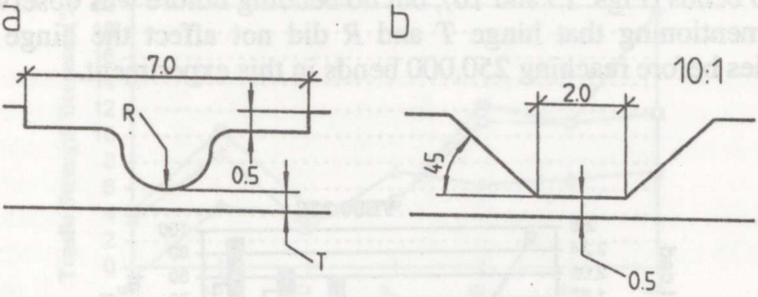

Fig. 11. Hinge web formed by radius (*a*) and shallow relief (*b*).

The results of the tensile test showed that a thicker hinge ($T = 1.0$ mm) was stronger in absolute values (load at max. load), but the calculations demonstrated that the tensile strength per hinge area (load/area at max. load) of the hinge with smaller hinge thickness ($T = 0.2$ mm) was stronger (Fig. 12).

These dependences can be explained by the melt flow and cooling time. The melt flow is more restricted if the hinge becomes thinner and molecules become more oriented. A thicker hinge has a longer cooling time than that of a thinner one after moulding, so the molecular relaxation time of a thicker hinge is also longer. The molecules of a thicker hinge had more possibilities to return to a non-oriented weaker form before "freezing in" due to a longer relaxation time.

In the case of virgin hinges, the difference in hinge thicknesses affected the hinge strength more than the change of radius. VB80 33C hinge strength (load at max. load, 0 bends) increased from 16 to 37% due to increased thickness at constant radius, and less than 4% due to a radius increase at constant thickness.

With regard to materials, at increased web thickness, with stronger materials, the absolute value of tensile strength doubled as compared to weaker ones. Also, one hundred initial bends influenced the tensile strength of a weaker material less than that of the best material (Fig. 13).

After one hundred initial bendings, the change of the tensile strength was greater with thicker hinges.

As predicted by theoretical calculations, the hinge tensile strength decreased after the initial bends. Smaller radius hinges of the same thickness were weaker (Fig. 13).

The results of the tear test were similar to those of the tensile test (Fig. 14). This figure shows that the hinge thickness-radius combinations affect the hinge tear strength similarly to the tensile strength.

Fatigue tests combined with tensile tests were performed for test specimens moulded from SB70 10K, the specimens were bent in the range of ±90°. The specimens were bent 2,500, 25,000 and 250,000 times for the first combined test series and 20,000, 60,000 and 100,000 times for the second combined series. No significant tensile strength decrease was observed before the first 100,000 bends. It decreased between 100,000 and

250,000 bends (Figs. 15 and 16), but no bending failure was observed. It is worth mentioning that hinge *T* and *R* did not affect the hinge fatigue properties before reaching 250,000 bends in this experiment.

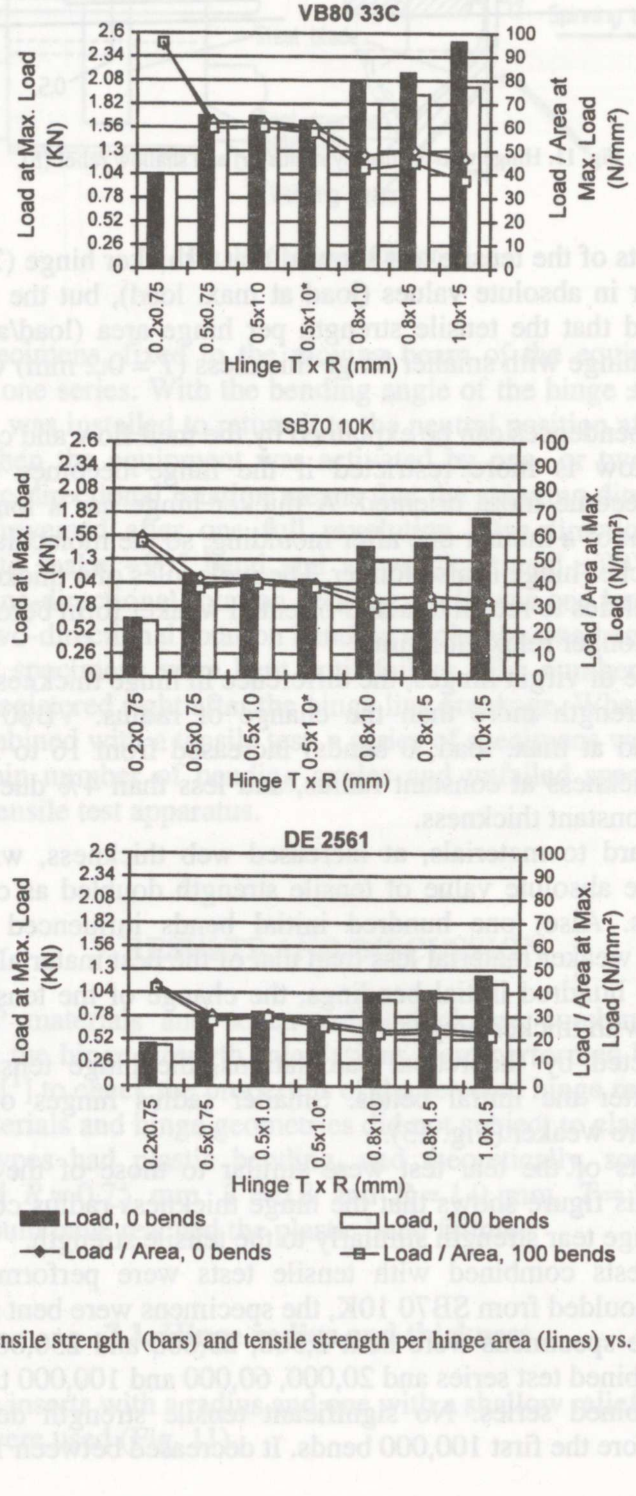

Fig. 12. Hinge tensile strength (bars) and tensile strength per hinge area (lines) vs. hinge geometry.

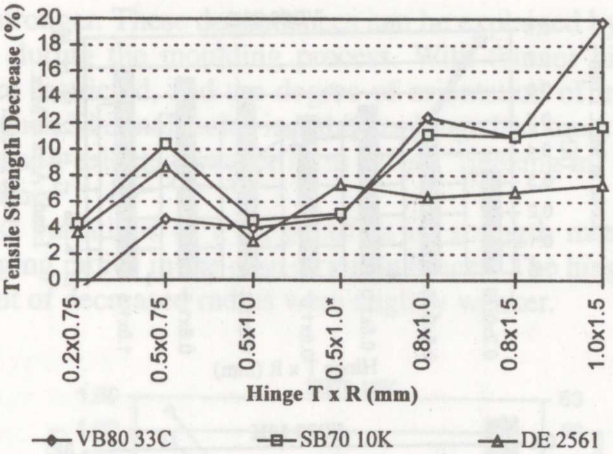

Fig. 13. Decrease of hinge tensile strength after 100 initial bends vs. hinge geometry.

A fatigue test to failure was performed using SB70 10K hinges, specimen bending angle was +90°. Five radius-thickness combinations were tested.

All the tested hinge geometry types resisted 350,000 bends without failure. A failure occurred between 350,000 and 550,000 bends. Here no significant differences between the bending resistances of hinges of different geometries were observed, and dispersion of the data was high. Thus, hinges with the largest thickness (0.8 mm) and the thinnest ones (0.2 mm) have higher bending resistance. The difference was insignificant between $T = 0.5$ hinges due to different radiuses and hinge forming types (Fig. 17).

3.2. Ends of the hinge web

The influence of the end geometries of the hinge web on tear strength was also studied. Two specimen types with three different hinge web ends were used in those experiments (Figs. 5 and 6).

Specimens with different hinge web ends were cut to half diagonally to the hinge line to make three hinge end geometries available for comparison. It was also possible to compare two identical end geometries ("one arc") moulded with different hinge inserts.

The tear test was performed after 0 and 100 hinge bends. The observed strength differences between "two arcs + one arc" and "straight + one arc" (Fig. 18) are probably due to small variation in the hinge thickness rather than to the hinge end geometries. Therefore, this study can neither support nor verify the conclusions presented in [4]. It was found that, as compared to a straight end, "two arcs" at a hinge end increase its tear strength considerably.

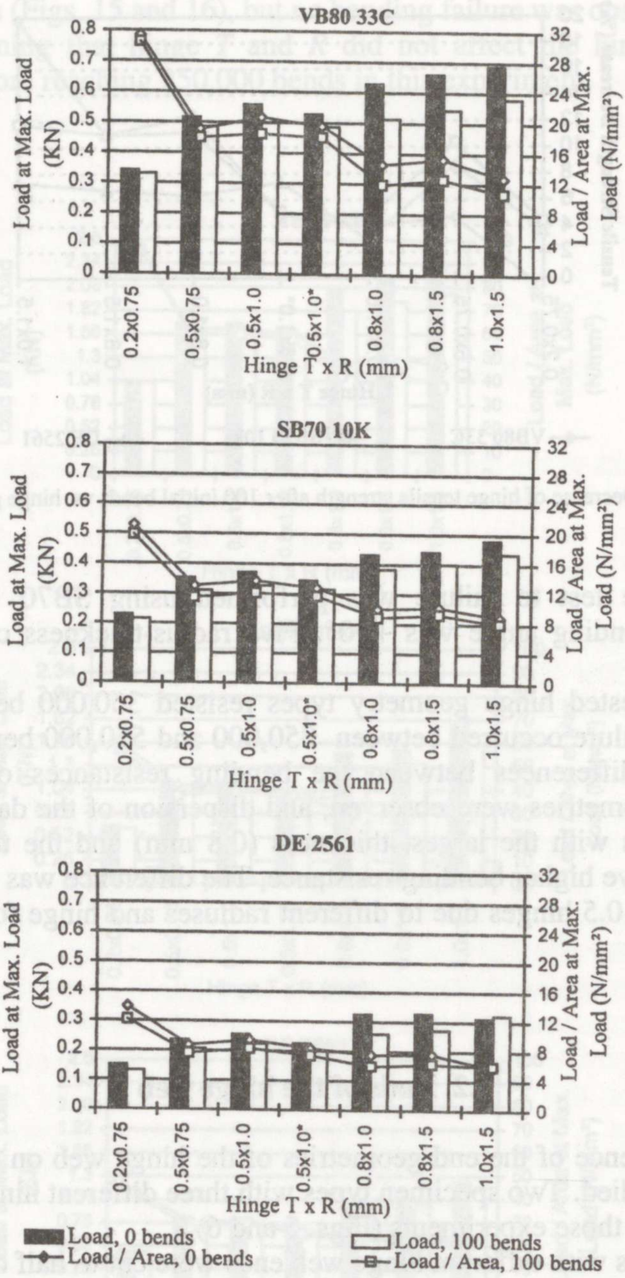

Fig. 14. Hinge tear strength (bars) and tear strength per hinge area (lines) vs. hinge geometry.

4. CONCLUSIONS

Correlations between the geometry and durability of a hinge were found.

Our tensile tests showed that thicker hinges are stronger in absolute values, but with respect to the tensile strength per hinge area, thinner hinges are stronger. These dependences can be explained by the behaviour of PP melt during the moulding process. With thinner hinges, the melt flow is more restricted, and the degree of orientation of macromolecules becomes higher. The molecules in a thicker hinge had more possibilities to return into a non-oriented weaker form before "freezing in" due to a longer relaxation time.

Thickness variations of a hinge affect its strength more significantly than a changing radius in the case of virgin hinges. The hinges of the same thickness but of decreased radius were slightly weaker.

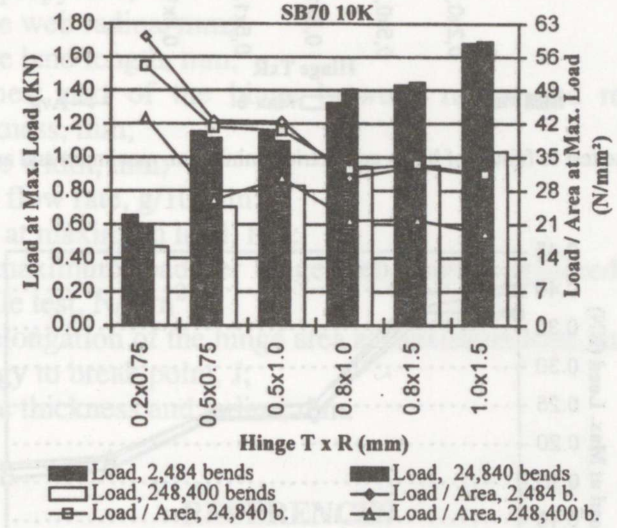

Fig. 15. The first fatigue test combined with tensile test vs. hinge *T* and *R*.

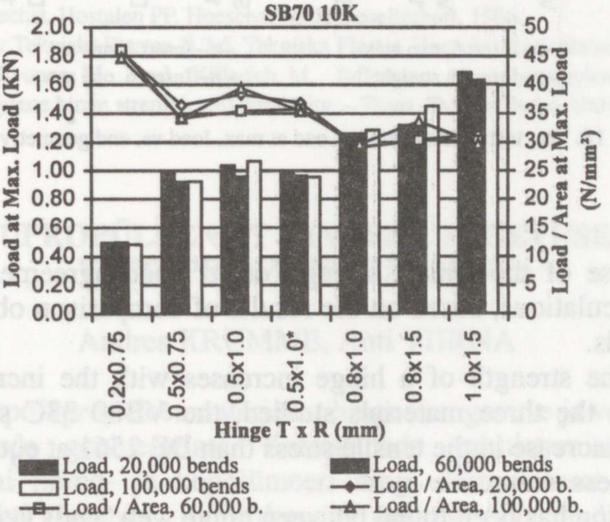

Fig. 16. The second fatigue test combined with tensile test vs. hinge *T* and *R*.

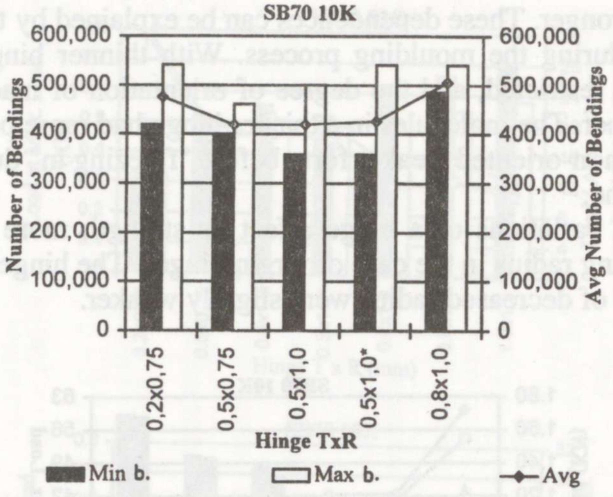

Fig. 17. Fatigue test to failure of hinge geometries: minimum, maximum and average values.

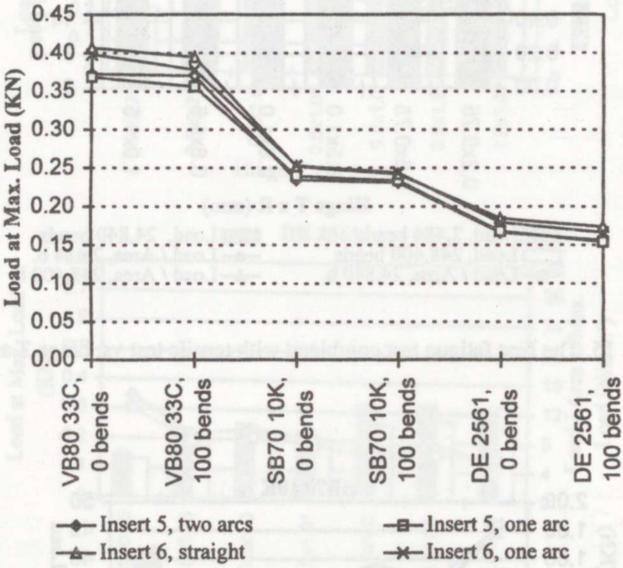

Fig. 18. Tear test of hinge ends. Load at max. load vs. end geometry.

The decrease of the tensile strength is in good agreement with our theoretical calculations, based on the results of comparison obtained after the initial bends.

Although the strength of a hinge increases with the increasing web thickness with the three materials studied, the VB80 33C shows about twice as large increase in the tensile stress than DE 2561 at equal values of the web thickness.

No correlation has been found between hinge web "ends geometry" and tear resistance.

ACKNOWLEDGEMENTS

The authors are grateful to Borealis Polymers Co for financial support and for the facilities provided for the experimental work in their laboratories. In particular, we thank Marko Sivonen and Mads Kiilerich for their supervision.

SYMBOLS

PP – polypropylene;
R – hinge web radius, mm;
L – hinge land length, mm;
T – thinnest part of the hinge between radius and relief, hinge thickness, mm;
H – hinge width, mm;
MFR – melt flow rate, g/10 min;
Lo – load at maximum load, KN;
Lo/W – the maximum load per hinge web length registered during the tensile test, N/mm^2;
DIS – the elongation of the hinge area at maximum load, mm;
E – energy to break point, J;
$T \times R$ – hinge thickness and radius, mm.

REFERENCES

1. Banister, R. A. Designing hinges that live. – Mach. Design, 1987, 59, 17, 103–106.
2. Neste Polypropylene. Injection Moulding Basic Techniques. Neste Chemicals, 1993.
3. "Propathene" for Integral Hinges. Imperial Chemical Industries, 1976.
4. Berube, A. R. Investigation of The Impact Strength of the Integral Living Hinge. Dissertation, University of Massachusetts-Lowell, 1993. UMI Dissertation Services, 1994.
5. Kunststoffe, Hoechst. Hostalen PP. Hoeschst Aktienbesellschaft, 1986.
6. Filmgångjärn Av Teknisks Plaster. B.3.5. Tekniska Plaster. Hoeschst Aktienbesellschaft, 1991.
7. Krumme, A., Sivonen, M., and Kiilerich, M. Influence of polypropylene materials to polypropylene hinge strength and durability. – Trans. Tallinn Techn. Univ., 1994, No 744, 107–114.

POLÜPROPÜLEENIST HINGEDE TUGEVUSE JA VASTUPIDAVUSE UURIMINE

Andres KRUMME, Anti VIIKNA

On uuritud polüpropüleenmaterjalist hingede tugevuse ja vastupidavuse sõltuvust nende geomeetriast. Katsekehade valmistamiseks kasutati polüpropüleeni homo- ja kopolümeeri ning elastomeerset kompaundi. Katseteks tehti erineva tööpiirkonna paksuse ja raadiusega ning mitmesuguse otste kujuga hingi. Määrati hingede tõmbetugevus, rebimistugevus ning vastupidavus pikaajalisele korduvale painutamisele. Lisaks sellele määrati tõmbetugevus ka pärast valitud painutustsükleid. Katsetulemuste põhjal leiti seosed hinge geomeetria, tema tugevuse ja paljukordsele painutamisele vastupidavuse vahel. Hinge paindele töötava piirkonna paksuse suurendamisega kaasneb hinge tõmbetugevuse kasv. Samal ajal väheneb suhtelise tõmbetugevuse väärtus hinge töötava piirkonna ristlõike pindala kohta. Hinge otste geomeetria ei osutunud hinge rebimistugevuse muutumisel määravaks faktoriks.