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Low Cycle Fatigue of PPS Polymer Injection Welds (I) -Fatigue Crack Behavior-

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An important class of short-fiber reinforced composites is the sheet molding compound, which is recently developed and currently used in many engineering applications. Fatigue failure of the composites is a subject of major concern in design and cyclic crack propagation is of particular significance in the fatigue life prediction of short fiber composites. However, research on the fatigue behavior of polymer injection weld, especially short glass fiber-filled polymer injection weld, has not been carried out. In this study the analyses of the fatigue crack growth behaviors at weld line and in the bulk are performed based on low cycle fatigue test.

Key Words : Polymer Composites, Fatigue Crack, Polymer Injection Weld, Crack Propagation, Polycarbonate, Polyphenylene Sulfide

1. Introduction

Many kinds of polymer composites are used for the primary materials of mechanically loaded structural elements. Injection molding processing is one of the most important procedures in manufacturing such parts made of thermoplastics. This process is caused by the weld line, formed when a flow front is separated into two parts by the presence of the pin and core in a cavity or by the difference in the thickness of flow path where they meet. Especially, the thermoplastic injection molding forms weld line due to the presence of the core, pin, corner and multiple gate that divide the polymer melt during flow in the mold and when injection molding complex parts, weld lines are often formed during the mold filling stage. This is a weld region where two flow fronts meet. These weld lines are well-known as a particularly critical region in the mold when mechanically loaded (Grafton, 1975 ; Tomari et. al, 1990). The investigation of the influence of weld lines on the mechanical properties and the morphology of injection molded parts has been an active area of research (Malguarnera and Manisali, 1981).

An important class of short-fiber composites is the recently developed sheet molding compound and currently used in many engineering applications such as automobile structures and components (Jutte, 1978 ; Heimbuch and Sanders, 1978). In general, these components and structures are subjected to repeated loading during service. Fatigue failure of the composites is, therefore, a subject of major concern in design (Riegner and

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Hsu, 1982) and cyclic crack propagation is of particular significance in the fatigue life prediction of short fiber sheet molding compound composites. While a large amount of study has been carried out for solving the problem of fatigue crack propagation in continuous-fiber composite laminates, the study of fatigue crack propagation in short glass fiber-filled polymer composites has not been extensive. Thornton (1972) and Owen and Bishop (1974) were among the first to study fatigue crack growth in short-fiber reinforced composites. Fracture mechanics concept was used to characterize fatigue crack propagation rate in discontinuous glass-fiber reinforced polymer composites. However, research on the fatigue behavior of polymer injection weld, especially short glass fiber-filled polymer injection weld has not been carried out.

Therefore, in this study the analyses of the fatigue crack growth behaviors at weld line and the bulk without weld line are performed based on low cycle fatigue test. Moreover, the effect of mold temperature on the fatigue behavior is investigated.

2. Experimental Procedure

2.1 Materials and specimen

The polymer composite material used in this experiment is polyphenylene sulfide (PPS) with crystalline structure having 40% short glass fiber content. The diameter of the glass fiber is 13 μm and its length is 200~400 μm. A double-gated mold, as is shown in Fig. 1, was used in this study. It is for a CT (Compact Tension) specimen with a parent and weld line. Four types of CT specimen (i.e. LP, TP, LW and TW), as shown in Fig. 2, are machined from injection plate for fatigue test. The mold conditions are listed in Table 1.

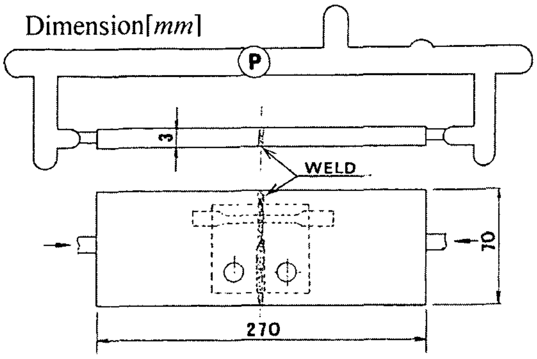


Fig. 1 Layout and dimensions of injection mold and specimens

2.2 Low cycle fatigue test

Crack propagation experiments are conducted on an automated low cycle fatigue machine. Thickness of the CT specimens was 3 mm. The CT specimens were precracked in accordance with the ASTM test method for constant-load-amplitude fatigue crack growth rates above 10^{-8} m/cycle.

Table 1 Fatigue test conditions

Molding Temp.	Factor	Parent		Weld	
		Parallel	Transverse	Parallel	Transverse
80℃	P_{max}(N)	400	500	400	400
	P_{min}(N)	40	50	40	50
	Frequency(Hz)	1.67	1.67	1.67	1.67
135℃	P_{max}(N)	450	550	450	450
	P_{min}(N)	45	55	45	22.5
	Frequency(Hz)	1.67	1.67	1.67	1.67

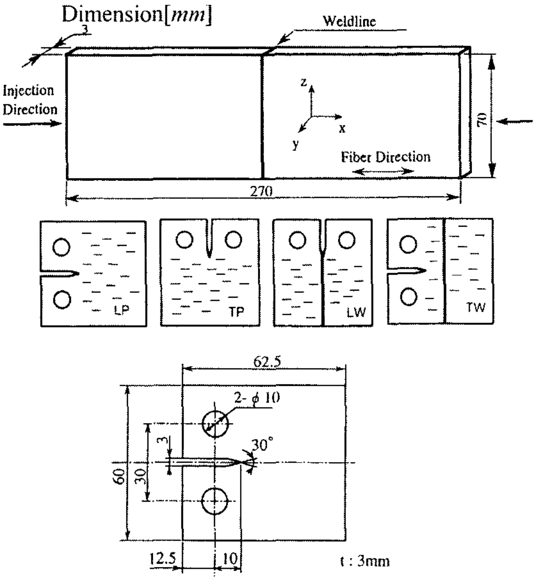


Fig. 2 Layout and dimensions of injection mold and extraction of CT specimen

Constant amplitude tests were obtained with load ratio, $R=P_{\min}/P_{\max}$, of approximately 0.1 and using a positive harversine wave with frequencies 0.017~1.67 as shown in Table 1. All tests were terminated when the crack growth rate became too great to measure the crack length accurately or when the uncracked ligament of the specimen $(w-a)$ ceased to be predominately elastic. Compact tension (CT) specimens were subjected to tension-zero-cycling under load control at room temperature, and crack growth was monitored with a traveling microscope, KRAK-gage and clip gage. Crack length, a, versus applied cycles, N, data were reduced to da/dN versus ΔK using a second order incremental polynomial method for constant amplitude tests.

The KRAK-gages used in this investigation had a gage length of 20 mm. The gage was bonded slightly ahead of the notch tip toward the front face of the specimen. At the beginning of each test, the output voltage of the gage was nulled by adjusting the calibration controls on the Fractomat instrument. Consequently, an initial reference reading was established on the digital display of the readout instrument. As the test progressed, the fatigue crack length was equal to the change of the reading plus the depth of the specimen notch.

In order to verify the crack length data developed by the KRAK-gages, a clip gage mounted on the front face of the specimen was used to monitor crack length by a compliance technique. Moreover, an optical microscope with x10 magnification was utilized for visual monitoring of crack extension.

2.3 KRAK-Gage instrumentation system for crack growth testing

This method, appropriately known today as the "KRAK-GAGE INDIRECTED POTENTIAL DROP TECHNIQUE", satisfies and exceeds the accuracy and sensitivity requirements of ASTM E647, the standard test method for fatigue crack growth rates (Bell et. al, 1979 ; Karger and Friedrich, 1988). Compared to earlier test methods, fully automated, uninterrupted computer controlled crack growth testing is easily accomplished.

The application of the KRAK-gage is totally independent of size, shape, material and conductivity of the test specimen and is, therefore, suitable for metallic, as well as for nonconductive specimens, such as ceramics, glass, plastics, concrete, etc.. The gage is essentially a thin, photo-etched, low resistance metal foil DC transducer of a certain geometry, adhesively bonded to a test specimen. The conventional, well-established strain gage installation techniques apply to surface preparation, cleaning and bonding of a KRAK-gage to test specimens.

A propagating crack in a test specimen will simultaneously propagate through the KRAK-gage and produces a relatively large increase in resistance of the gage. Excitation of the KRAK-gage is provided by an adjustable precision constant current source in the FRACTOMAT. This basic measuring technique is known as the "Indirect DC Potential Drop Method". A yet uncracked KRAK-gage will produce an initial drop or output in the gage of 88.8 mV(DV). This initial potential drop or output voltage is firstly amplified in a low gain amplifier to 0.888 V and then is balanced or nulled against an internal precision reference voltage of 0.888 V by simply adjusting the constant current excitation.

3. Results and Discussion

3.1 Fatigue crack behaviors

Several fatigue crack tests are conducted. Throughout the test, the crack length is monitored by the gage attached on one side of the specimen and measured visually with a ruler and moving telescope on the opposite side at the same time.

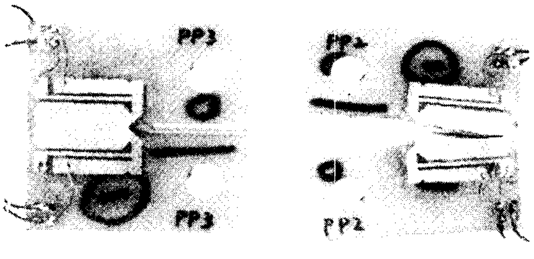


Fig. 3 Fatigue crack specimen instrumented with the KRAK-gage

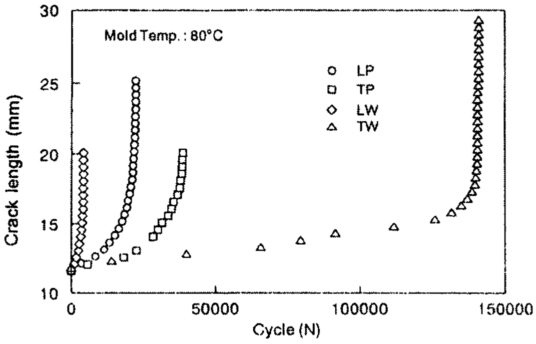


Fig. 4 Fatigue crack growth curve for each material conditions of PPS parent and weld

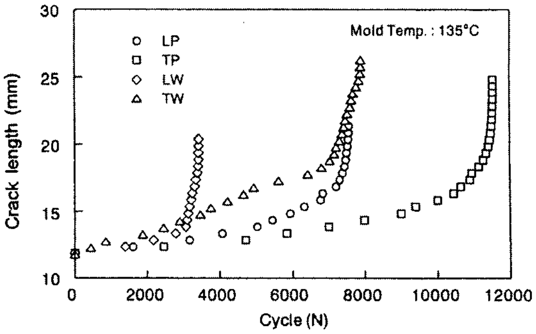


Fig. 6 Relation between crack length and applied cycles of four different specimens

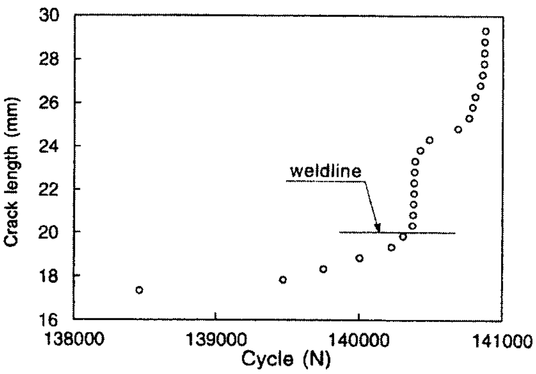


Fig. 5 Crack length applied cycle curves at the last part of TW

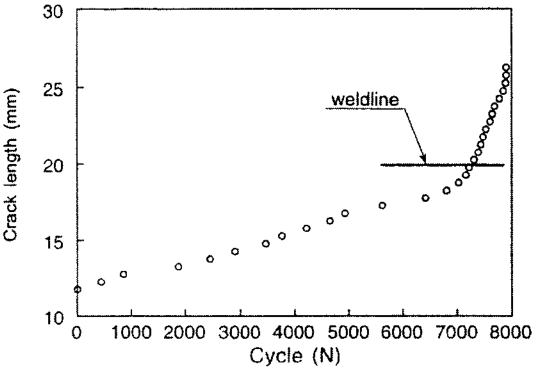


Fig. 7 Relation between crack length and applied cycles of TW at 135℃

Figure 3 shows specimen instrumented with the KRAK-gage and the fatigue crack specimen after testing.

Figure 4 shows the relation between crack length and applied cycles of PPS parent and weld molded with injection mold of 80℃. The fatigue life of TP and TW is longer than that of LP and LW respectively at parent and weld. This result proves that fatigue crack growth is retarded because the fibers intersected the direction of crack growth. The change of crack length versus applied cycles at the last part of TW is magnified in Fig. 5. This curve shows the growth of crack and storing the energy by crack closure up to weld line. But the crack growth after weld line is jumping due to breaking the fiber of weld line perpendicular to the direction of crack growth.

Figure 6 shows the relation between crack length and applied cycles for mold temperature of 135℃. The fatigue crack growth behavior of TP, transversed parent, is longer than that of TW and LP, affected by the mold temperature, but crack growth of LW is the shortest among parent and weld of four different specimens due to softness to adhesive force in weld.

Full curve is shown in Fig. 7 for TW with weld line which is perpendicular to the direction of crack growth. Crack growth is retarded in the front of weld line and the crack grows rapidly after breaking the glass the fiber oriented perpendicular to the direction of crack growth.

3.2 Fatigue crack growth rate behaviors

Figure 8 shows the relation between fatigue crack growth rate, da/dN versus ΔK curves for the four different specimens. In this figure, the fatigue crack growth rate, da/dN, of LP, TP and LW, smoothly increases.

Figure 9 shows the relation between fatigue crack growth rate, da/dN versus ΔK curves for

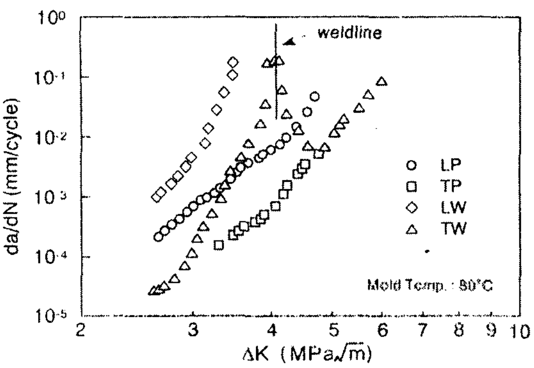


Fig. 8 Fatigue crack growth verse ΔK for each material conditions of PPS parent and weld

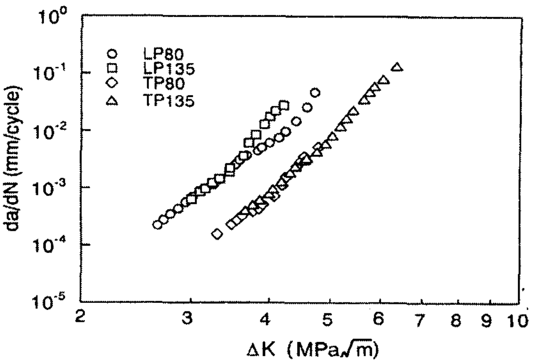


Fig. 10 Relation between da/dN and ΔK of LP and TP

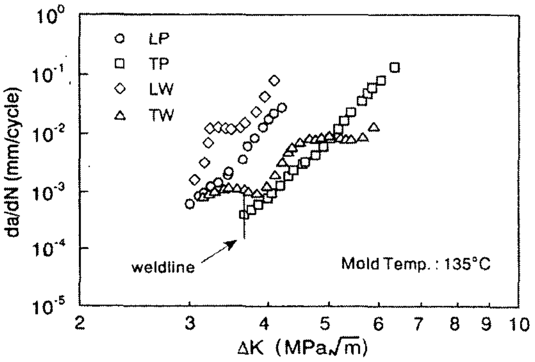


Fig. 9 Relation between da/dN and ΔK of four different specimens

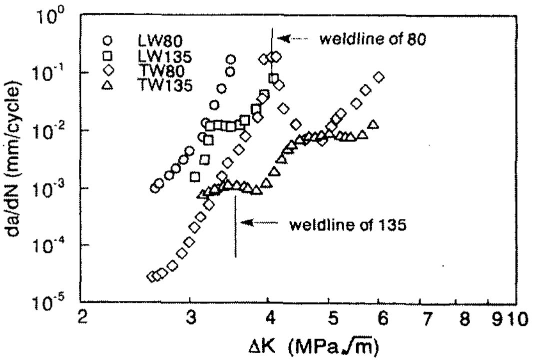


Fig. 11 Relation between da/dN and ΔK of WP and TW at mold temperature of 80℃ and 135℃

the four different specimens injected at mold temperature of 135℃. The fatigue crack growth rate increases in the order of TP, TW, LP, LW, the result of *da*/*dN* is influenced bythe fiber orientation. Especially, TW curve shows the jump and retardation due to weld line changing the fiber orientation.

3.3 The effect of mold temperature

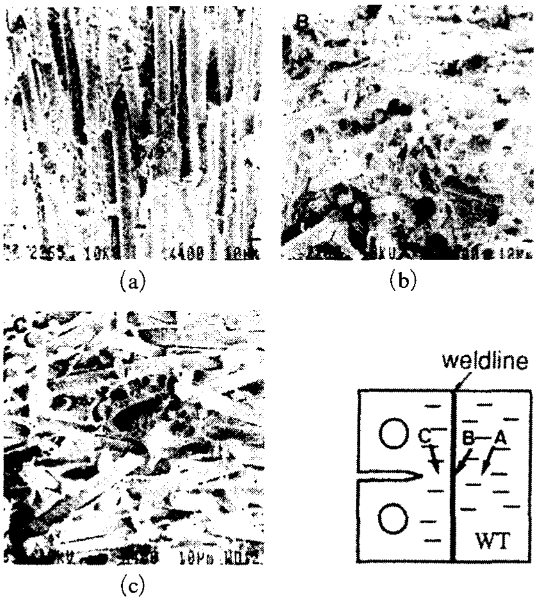
In polymer injection, fiber orientation is influenced by mold temperature due to difference of cooling rate between the inside and outside of molding. In this study, mold temperatures were 80℃ and 135℃.

Figure 10 shows the relation between *da*/*dN* and the *ΔK* of LP and TP at the mold temperature of 80℃ and 135℃. There is no great difference in fatigue crack growth rate according to mold temperature of 80℃ and 135℃. Mold condition makes difference of fatigue crack growth rate by 10 times due to the fiber orientation. The fiber orientation of LP and TP specimen is mutually perpendicular. The fiber orientation of LP is parallel and TP is perpendicular to the direction of crack growth.

Figure 11 is the relation between *da*/*dN* and the *ΔK* of LW and TW at the mold temperature of 80℃ and 135℃. Fatigue crack growth behavior of weld line is affected by fiber orientation and mold temperature. Especially, the weld line property at TW which is perpendicular to the direction of fatigue crack growth is the jump and retardation of fatigue crack growth rate.

3.4 SEM observation of fracture surface

Figure 12(a~c) shows a typical fractography of fracture surface in TW of PPS. Figure 12(a) shows the fracture surface far from weld line.



(a) (b) (c)

Fig. 12 Fracture surface for obserbation of fiber orientation along fatigue crack growth

The fiber oriented along by the surface and the matrix traces extracted the fiber are observed. It is inferred to grow the crack by debonding between fiber and matrix or fracture of the matrix in itself. Figure 12(b) shows the fracture surface of middle area at weld line. Fiber orientation is perpendicular to crack growth direction and shows the mark pulled out the fiber. Crack growth mechanism at weld line is the fiber breaking and extraction first and the matrix fracture next. Figure 12(c) shows the fracture surface around the weld line, mixing zone. Fiber orientation is complexed in three-dimensional direction. Fatigue crack growth behaviors can be discussed by fracture surface and fatigue test, as follows.

In any PPS material, the fatigue crack growth behaviors of LP specimen (the MFD is parallel to the direction of fatigue crack growth) are independent upon the fiber orientation and the crack smoothly grows. However, the others specimen, TP, LW, TW, are dependent upon the fiber orientation, preventing crack growth. These behaviors also appear at $da/dN\text{-}\Delta K$ curves. Especially TP and TW with weld line perpendicular to crack growth direction show an inflection at $da/dN\text{-}\Delta K$ curves. Kunz and Beaumont (1975) reported that $\log(da/dN)\text{-}\log(a)$ of FRP shows an inflection curve under compressive fatigue test. They observed the microcrack growing along the main crack. The direction of crack growth is dependent upon interface strength of fiber and matrix. Crack growth rate is stopping or retarding according to the combination of material. Lim and Kim (1993) investigated the fatigue properties of chopped strand glass mat/polyester composite in synthetic sea water. And then $da/dN\text{-}\Delta K$ curves were divided into two regions; one decreased with the crack extension and the other increased with the crack extension. This is the transition point occurred during the crack propagation shifted to high ΔK value as load increase.

Ohji et. al (1980) reported the result of fatigue crack growth and closure with $da/dN\text{-}\Delta K$ curves, inflection curve. They suggested that fatigue crack growth behaviors of clad plate with two kinds of different plates include the jump and retardation of ΔK. Erdogan (1972) studied that K value decreases at high material of Young's modulus among two kinds of bonding materials, and at the opposite K value increases.

The weld line of this study represents the bonding of two kinds of different materials. Thus, the study considers fiber orientation and density at TW and increasing Young's modulus around the weld line. These parameters are assumed to jump and retard the crack growth rate.

4. Conclusions

The summary derived from the experimental results on the fatigue crack growth behaviors of PPS injection weld are summarized as follows.

(1) The relation between crack length and applied cycles measured with clip gage, KRAK-gage and optical method is nearly same, so can be measured and discussed by KRAK gage with merit to acquisite the data.

(2) Fatigue strength of LW having weld line paralleled to the direction of crack growth is the lowest. TW and TP are the highest fatigue strength at mold temperature of 80℃ and 135℃, respectively.

(3) Fatigue crack growth rate of LW which the weld line is parallel to the fatigue crack is similar to that of LP parallel to the crack and increasing linearly. But fatigue crack growth of TW and TP is dependent upon flow front of injection mold and has inflection point during the crack growth.

(4) Fatigue crack growth behaviors of TW having weld line transversely is similar to that of LP under the weld line, and retarding around the weld line. After that, fatigue crack growth behaviors of TW is same to TP.

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