JOURNAL OF MATERIALS SCIENCE MATERIALS IN MEDICINE 3 (1992) 88–94

An evaluation of the use of infrared heating for contouring 30% short carbon-fibre-reinforced PEEK

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The ability to contour reinforced composites at specific points would allow these low modulus, high strength materials to be utilized in a wide variety of new applications. Contourable materials of this type would be especially suitable for orthopaedic applications such as internal fixation of fractures where plate removal due to stress shielding and bone resorption are major concerns. To this end, the high-temperature contourability of 30% short carbon-fibre-reinforced PEEK was investigated. The use of infrared radiation to heat this material to temperatures suitable for contouring was developed and refined into a protocol for heating and bending 12.4 × 6.4 mm injection-moulded flexural testing bars. To evaluate the heating, contouring and cooling effects of this processing on the material's mechanical and physical properties, five specimen groups were tested: control, extended heat only, cyclical heat only, repeated contouring, and repeated contouring-quenched. Each group's flexural properties, fracture toughness, post-contouring matrix crystallinity and extent of fibre-matrix wetout were monitored.

The two heat only groups showed no significant changes in any properties compared to control. For the contoured groups, the quenched subgroup showed a minimal 0–9% decrease in all categories. The non-quenched group showed only a 0–6% change. The resilience of short carbon-fibre-reinforced, PEEK after severe thermo-mechanical cycling is convincing evidence of this material's suitability for structural applications, especially in which contourability and fast processing are required. This study demonstrates the thermoductility of CFR PEEK.

1. Introduction

Metallic devices are often used to facilitate the healing of bones in humans and animals. Two main concepts for such a device are envisioned. The first of these is rigid fixation, using a high modulus material such as a metal to immobilize the fracture site. Although effective in the short term, rigid fixation has been shown to cause osteoporosis of the bone after several months from stress-shielding effects due to the high modulus of metallic fixation plates relative to that of cortical bone [1, 2]. The normal preventative measure for this condition is a second operation for removal of the plate after several months.

The second concept outlines the use of a material with a modulus near or below that of bone, greatly reducing stress shielding, and encouraging a more natural healing process. Such an effect has been demonstrated by Gillett *et al.* [3] by using fibre-reinforced nylon plates and metal screws. Jockisch *et al.* demonstrated that fracture fixation plates made from 30% short carbon-fibre-reinforced PEEK facilitated effective healing of beagle femur osteotomies in 8–12 weeks [4].

The major limitation of polymer composites in this application is that composites with suitable strength and fatigue life usually have a low strain-to-failure. Thus complex-shaped fracture sites such as the ankle and spine, which require significant contouring in the operating room, precludes the use of most composites. Thermoplastics and their composites, however, can be softened near their melting temperatures, reformed, and cooled again in new shapes. This was demonstrated in a study by Brown *et al.* [5], where short carbon-fibre-reinforced polyester, polysulphone and PEEK demonstrated high temperature contourability, or thermoductility. The reinforced PEEK could be contoured to the greatest extent of the three materials evaluated. PEEK is a semicrystalline thermoplastic with a T_g of 145 °C and a melting point of 334 °C [6]. It is resistant to the effects of most common solvents, and, as stated by Jones *et al.* [7], "PEEK can be processed using the widest variety of methods and, as a result, is suitable for a broad selection of engineering applications." It is available in unreinforced form, as well as short fibre and continuous fibre reinforced preparations.

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This study undertook the development of an infrared radiative heating device and reproducible processing protocol which would permit localized contouring of bar-shaped 30% short-carbon-fibre-reinforced, or SCFR, PEEK. A study of the effects of high-temperature contouring was achieved by monitoring four properties to check for changes in the material due to processing: flexural properties, fracture toughness, matrix crystallinity by using DSC, and a qualitative matrix wetout determination by using SEM. These four evaluations were intended to provide a suitable diversity of physical measurements to study the effects of the contouring and heating from a broad materials science perspective. Through this study, the thermoductility of this material and the viability of an infrared heating system for contouring composites was demonstrated, and clinically relevant contouring of a fracture plate-like bar was achieved.

2. Materials and methods

The material used in this study was an injection-grade polyetheretherketone, or PEEK, matrix filled with chopped Hercules AS4 carbon fibre at 30% by volume (ICI Victrex 450CA30). This material was injection moulded in a single batch, forming 200 flexural test bars with dimensions $125 \times 12.4 \times 6.4$ mm (Dexter Composites, Cleveland, OH). The flex bars showed fibre orientation differences between core and skin regions typical of injection-moulded, short-fibre-reinforced specimens, but more importantly showed good consistency in appearance along most of the length of the bar.

Two infrared heating units (Innovative Industries, Inc., Cleveland, OH) were used to heat specimens for contouring. Each unit was composed of a 50 mm $\times$ 150 mm $\times$ 250 mm stainless steel shell lined with 25 mm thick blocks of ceramic refractory insulation. The lined shell configuration created an internal heating chamber 54 mm deep $\times$ 105 mm wide $\times$ 140 mm long. This chamber served to direct the IR radiation to the open bottom face of the unit where the specimens were placed. Each unit could accommodate up to six 150 mm long infrared bulbs, although only two bulbs were used in this experiment to localize heating. The bulbs were mounted in the endplates of the heating unit, and extended lengthwise across the back of the heating chamber. The perpendicular distance from the bulb axis plane to the bottom (open) plane of the unit was 45 mm. Each unit had a top-mounted fan whose function was to keep the quartz bulb end terminals cool to avoid melting the solder connections to the wiring. The fans did not effect the heating process in any way.

The two heating units were set up facing each other to allow specimens to be heated from two sides simultaneously. To minimize heat conduction from specimens, both specimen ends were set on thin refractory blocks, suspending them in the air. To standardize bulb-to-surface distances, refractory block was used to space the two units such that the specimen faces were located 62 mm from each bulb axis plane.

The quartz heat lamps (Model No. H500T3, General Electric) were rated at 500 W at 120 V, with a maximum temperature of 1000–3000 °C. The heat generated by these bulbs was solely infrared radiative transfer from the hot quartz bulbs to the exposed cooler surfaces such as the heating chamber refractory insulation or specimens at the heating chamber opening.

A thyristor power regulator (Series PAC10, Shimaden Co.) was used to regulate current flow to the bulbs. The main function of this regulator was to prevent an initial current surge to the heat lamps when they were cold. At room temperatures, the bulbs have very low resistance, and would allow a current surge to pass through them which could burn out both the bulbs and regulator. The thyristor delays the current rise over 1–2 s to allow the bulbs to develop higher internal resistance as they heat, thus becoming essentially self-protective against current surges. In addition, a rheostat attached to the power regulator allowed direct control of the voltage across the parallel-wired heating units, and thus regulated bulb intensity.

Temperatures were monitored using a full-length CFR PEEK flex bar with a small diameter T-type thermocouple probe inside the core of the bar and a thermocouple thermometer (Cole-Palmer Co., Model no. 8528-10). To achieve this, an access hole was drilled (no. 57 drill) into the side of the flex bar at its centre, halfway across the width in depth. The hole was just large enough to create a snug fit around the inserted insulated thermocouple wire. This flexural test bar/embedded thermocouple assembly will be referred to hereafter as "the monitor twin".

To produce small-radius contours at specific points on a flex bar, heating had to be localized. To achieve this, flex bars were positioned perpendicular to the bulbs, heating the centre 5 cm in a maximum irradiation field. To eliminate variations in irradiation along the bulb axis, a consistent position in the heating chamber was selected for specimen placement. To expose specimens to a uniform radiation field, specimens needed to be positioned away from the side walls. To place the monitor twin and one specimen symmetrically in the heating chamber, both were placed 33 mm from the end walls.

2.1. Heating protocol

A series of exploratory experiments were undertaken to optimize a heating protocol. Both one-sided and two-sided heating were investigated. Two-sided heating was chosen for this study since specimens could be heated more uniformly and much more quickly from both sides simultaneously. Two variables, peak core temperature and heating rate, were studied to optimize high-temperature specimen contourability while minimizing surface melting on faces exposed to IR radiation.

After experimentation with peak core temperatures ranging from 280 to 315 °C using heating rates ranging from 1 to 4 min heatup time, a protocol which allowed contouring of 10° without surface melting was selected. It was found that an initial annealing with

slow heating to 280 °C and holding for 3–4 min improved the resistance of the material to melting. The protocol used for all subsequent experiments consisted of a two-stage heating cycle, using an initial heating step to 280 °C core temperature in 2.5 min, followed by a stable step at 280 °C for 1 min. The stable step was included to allow the flex bar to reach a uniform temperature across its entire thickness before contouring.

2.2. Experiment

A stainless steel plate-bending press (Acromed, Cleveland, OH) was used to contour selected specimens. Two 18.5 mm diameter steel posts 40 mm on centres and a lever arm-activated nosepiece were used to contour heated specimens in three-point bending. Using specimens bent to 0, 8, 10, and 18° deflection, the nosepiece was marked to allow consistent degrees of contouring. Extent of bending was measured by tracing the contoured pieces and measuring the tracing with a protractor.

The effects of heating, contouring and cooling method on the material properties of the 30% SCFR PEEK were the most important concerns in evaluating the IR heating method. Four protocols, extended heat only, cyclic heat only, repeated contouring, and repeated contouring-quench were developed to determine heating and contouring effects on material properties of specimens heated to a core temperature of 280 °C as compared with a 10-specimen control group. Core temperature versus time data were collected for each cooling protocol, both with and without a contouring operation. The maximum cooling rate for each process, measured over a 5–10 s interval, is shown in Table I.

The system of notation used to denote the protocols used in this study was in the form "number–letter–letter". The number was the degree of contouring applied to the specimen during processing. An "R" as the first letter indicated that the heating was in repeated cycles. The last letter indicated the cooling method used between cycles. "S" designated slow cooling; the specimen was left in the heating unit chamber to cool slowly to room temperature after turning off the power. "T" designated table cooling; the specimen was placed on the lab table immediately after removal from the heating chamber or after bending the specimen in the press for 60s. "Q" indicated quenching in saline immediately after removal from the heating chamber or after bending the specimen in the press for 60 s.

TABLE I Maximum cooling rates for the three cooling methods: S, slow-cooled; T, cooled on tabletop; and Q, quenched in 25 °C saline

Method	Point in process	Max. rate (°C min^{-1})
S	directly after heating, leave in warm oven	90
T	directly after heating	210
	after 60 s in press	180
Q	directly after heating	700
	after 60 s in press	400

The first group, designated 0S, was subject to a short-term, heat only exposure of 20 min at 280 °C core temperature and cooled in the chamber to room temperature. The second group, 0RT, was subject to an annealing cycle, cooled on the lab table to room temperature, then heated using the two-stage heating protocol and cooled on the lab table 13 additional times with no contouring. The 0RT group was intended to act as a heat-effects-only control for the groups which were contoured.

The third group, 10RT, was annealed, then heated and cooled as in the "R" method with the following addition: after the first heating, the specimen was contoured 10° at its mid-section, held in the bending press for 60 s, and cooled on the lab table. Ten minutes later, the specimen was heated a second time and then cooled without contouring on the lab table. The contour was then remeasured to monitor relaxation upon reheating. After the next heating, the specimen was contoured in the *opposite* direction to 10°, and after cooling was reheated again. The contouring and relaxation operations were alternated for 12 heating cycles, with each 10° contour in the opposite direction to the previous one. The final heating was a straightening operation. These specimens were subjected to a total of 14 heat cycles including six contours.

The fourth specimen group, 10RQ, was subjected to the same process as the 10RT group except that all cooling was achieved by quenching in room temperature saline immediately after 60 s in the bending press or after reheating.

An ANOVA test was conducted to compare the contours achieved in each step of the 10RT and 10RQ process groups. No two specimens' mean deflections showed a statistically significant difference when compared with the mean deflection for the six specimens in each group. This indicates that the contouring process was consistent and thus not a variable in the material property evaluations.

2.3. Test methods

Flexural testing was conducted in three-point bending following ASTM D790M using a universal testing machine (Scott-CRE/1000) with a 4900 N load cell and 3.25 mm radius aluminum supports and nosepiece. Using a span-to-thickness ratio of 16:1, the span was 101.6 mm. Crosshead speed was set at 2.7 mm min^{-1}, selected to create a strain rate of 0.05% strain min^{-1}. All specimens were tested with the same orientation relative to the nosepiece.

For fracture toughness, specimens were prepared and a test method selected to follow the ASTM E399 protocol. This K_{IC} determination for metals has been utilized for polymers and composites in several studies [5, 8, 9]. Twenty specimens were prepared by cutting a narrow access slit in each specimen halfway (6.10 mm (0.240 inches)) into the specimen. A sharp crack extension was cut into the bottom of each access slit using a

razor blade, with total depth of the access slit and crack extension not exceeding 55% of the specimen width. To meet all conditions of the ASTM E399 standard, specimens were placed on two aluminium stands centred 49.6 mm apart and tested in three-point bending at a crosshead speed of 10.0 mm min^{-1}. This produced a rate-of-stress increase of approximately 2.0 MPa $m^{1/2}$ s^{-1}. After analysis, all specimens in this study fulfilled the conditions outlined in ASTM E399 for considering calculated K_Q values determined in testing to be a fracture toughness values, K_{IC}.

To determine whether there were any changes in matrix crystallinity, small samples from the outer 1 mm layers of specimens from each group were sectioned to 2 mm back from the fracture surface plane. Selecting material for analysis in the above manner insured two things. First, the samples were composed of the material areas exposed to the highest irradiation, and therefore the highest temperatures. Second, the strips were from near the fracture plane. This implied the material would have suffered the maximum effects of the mechanical deformation applied during contouring. The material tested, therefore, was representative of the most severe effects of the processing.

After sectioning, each group's material was chopped, weighed to the nearest 0.01 mg with a microbalance (Mettler), and separated into 6–10 mg samples of multiple or single pieces. Each sample was crimped inside an aluminium sample pan for testing. Crystallinity was determined with a differential scanning calorimeter (DSC) using a Perkin-Elmer DSC 7 with an instrument controller (TAC 7, Perkin-Elmer). Each heating scan was run from an 80 °C starting temperature to a 400 °C final temperature at a 20 °C min^{-1} heating rate, a common testing protocol [6]. A baseline was run at the start of testing following the same heating conditions and using an empty sample pan. All analyses of exothermic peak areas were performed using the TAS 7 software on a Model 7500 Lab Computer (Perkin-Elmer). By using a formula derived from an equation by Seferis [10], the mass fraction of crystalline matrix in each group's sample was determined. By dividing this number by the mass fraction of matrix in the composite sample, the mass fraction of matrix which was crystalline can be determined. This quantity was standardized for amount of matrix in each sample.

Fracture surfaces were examined using a scanning electron microscope (JEOL JXA-840 Scanning Micro-analyzer). Photomicrographs of selected fracture surfaces from each specimen group were taken to represent common fracture surface features seen after each protocol, and these representative photomicrographs were qualitatively compared for changes in fibre-matrix morphology.

3. Results

The results of flexural testing, and fracture toughness and crystallinity determinations for the control group and four two-sided heating specimen groups are displayed in Table II. Mean strengths for all specimen groups show less than a $\pm$ 3% change in magnitude, indicating that strength is not affected by IR heating for these protocols. Because of the high reproducibility of the protocols and low standard deviations, however, two of the strengths are statistically different from control at a significance $p < 0.05$. The strength of the 0S heat only group was increased (+ 2%), and that of the 10RQ repeated contour-quench group was decreased (− 2.5%). Mean strains for the two heat only groups did not decrease from control strains (− 2%, NS). The 10RT repeated contour group showed a 5% decrease from control ($p < 0.05$), and the 10RQ group a 9% decrease ($p < 0.05$). The flexural modulus was not affected by any protocol, with changes that ranged from + 1 to + 3%. The 18.7 GPa modulus for the 10RT group showed a small (+ 3.3%) increase over the 18.1 GPa for the control group ($p < 0.05$).

The fracture toughness results for the 0S specimen group showed that K_{IC} was unchanged from control values. The 10RT group mean K_{IC} decreased a minimal 6% from the control mean K_{IC} (NS). The 10RQ mean K_{IC} was 9% lower than CONTROL ($p < 0.05$), the only statistically significant change in K_{IC} with any of the processing treatments. The crystallinities of the material after all protocols were also close to the same. An ANOVA was conducted on the four specimen groups' mean crystallinity mass fractions. No significant difference between any two groups' means was detected. This lends support to the statement that there was no change in matrix crystallinity due to any of the applied protocols (heating, bending or quenching). Comparison of representative SEM photomicrographs uncovered extensive fibre-matrix bonding extending across the entire surface of all specimens, with only a slight thinning of wetout thickness in the contoured groups.

TABLE II Results of material testing after all five IR heating and contouring protocols, expressed as mean (standard deviation)

	n	Strength (MPa)	Strain (%)	Modulus (GPa)	K_{IC} (MPa $m^{1/2}$)	Crystallinity (%)
CONTROL	10	314 (4)	2.28 (.08)	18.1 (.4)	9.3 (.34)	43.8 (1.2)
0S	5	321 (7)[a]	2.24 (.07)	18.4 (.6)	9.4 (.62)	44.1 (1.2)
0RT	5	323 (10)	2.24 (.05)	18.6 (.5)	ND	44.4 (2.4)
10RT	5	315 (5)	2.16 (.06)[a]	18.7 (.4)[a]	8.9 (.44)	45.5 (2.7)
10RQ	5	306 (6)[a]	2.08 (.07)[a]	18.3 (.3)	8.6 (.18)[a]	42.5 (2.3)

[a] Significant at $p < 0.05$.

4. Discussion

Preliminary optimization studies showed that peak temperature, heating rate and thermal history had significant effects on how much thermal and mechanical alteration occurred during processing. The peak core temperature and specimen heating rate at which damage from heating would be minimized (at lower temperatures) and yet where the proposed 10° contouring could be made without mechanical damage (more of a problem at lower temperatures) were also sought to better define the processing window. Peak core temperatures above 300 °C, regardless of heating rate, produced visible degradation on exposed faces. Two-sided heating allowed much faster heating rates at lower power levels compared with one-sided heating. Heating rates which reached 280–290 °C core temperatures in under 2 min tended to cause softening or surface puffing in the outer specimen layers. As a result of these observations, heating rates to peak temperature were designed to be longer than 2 min. Although a peak core temperature of 290–295 °C was suitable for the desired 10° contouring and produced little surface disruption at low heating rates, it was decided to heat to 280 °C peak core temperature to provide a margin for overheating error and to reduce the total heating time to temperature.

To check for annealing effects, a flex bar was cut in half. One half was heated from two sides. It underwent a surface appearance change from shiny to matt, and developed a slightly fuzzy texture. After cooling, both were placed in the heater. Both specimens were heated until the untreated half suffered severe blistering on both faces. During this heating, the first half suffered *no additional degradation*, apparently due to changes caused by its first heating. This observation is supported by previous studies where PEEK annealed at temperatures from T_g to near T_m showed a small melting peak 10–15 °C above the annealing temperature when scanned with DSC [11, 12]. The probability that the 280 °C peak core temperature was instilling a small amount of matrix with the ability to resist slightly higher temperatures meant that the differences between core and surface temperatures during processing, under slower heating rates, might be tolerable if the material was first annealed to processing temperature. As a result, an annealing cycle before processing was added to incorporate this resistance before contouring. This consisted of heating a specimen to 280 °C using non-degrading heating rates (2.5 min) and holding it there for 2–3 min.

Having proven the potential for low degradation and substantial contouring, issues pertinent to the applicability of the process for clinical contouring of fracture plates were considered. For long bones and some curving skeletal sites, a contour in the 10° range is enough. Repeated heatings and contourings to each specimen, the "R" protocol, was chosen as a simulation of multiple attempts in the operating room to contour a device to fit an anatomical site. The need for fast cooling in the operating room was incorporated as the saline quenching, or "Q", cooling method. Incorporating these concerns into the processing protocols adds an applied technology dimension to this study, since the composite had the shape of a fracture plate and was contoured under several clinically relevant conditions.

4.1. IR heating unit

The infrared heaters demonstrated several qualities desirable for a heating and contouring system for composites, including possible use for contouring fixation plates in the operating room. First, the hot zone for the IR heating assembly was fully contained within the unit, minimizing environmental disturbance and safety risks to the operator. Direct operator involvement was needed only for transfering the hot specimen to the press and pulling the bending arm on the press. Specimens were heated and contoured without complication, therefore, and sterile instruments could have been used as well. Lastly, this equipment provided a large processing window of reproducible heating levels and rates which would be available for a variety of polymers and composites, specimen thicknesses and desired contouring levels.

In terms of attaining a non-degrading heating protocol, two-sided heating protocols were successful. Neither thermal exposure for 20 min at 280 °C core temperature (0S) nor 14 heat cycles to 280 °C (0RT) had any negative effects on the material; in fact, strength at failure increased 2 and 3%, respectively. Fracture toughness and matrix crystallinity did not change for either group, and SEM analysis revealed no changes in fracture morphology or fibre wetout compared to control.

The repeated contouring specimens, 10RT, were subject to an extremely severe mechanical test: heated then bent to 10° deflection in opposite directions six times with thermal cycles between each contouring. These specimens suffered no loss in strength or modulus, and only a 5% decrease in strain at failure. Fracture toughness showed a slight decrease of 4%. Matrix crystallinity was also unchanged, even though all samples were taken from the region of hottest exposure and greatest mechanical strain. Fibre-matrix wetout was still intact after processing. With a trained operator, very few applications will require more than two or three attempts to contour a device at a given location, and then rarely in opposite directions. Surviving this worst-case mechanical treatment protocol demonstrates that 30% SCFR PEEK has definite potential for contouring applications.

The 10RQ specimens were subject to a whole series of operating room-like requirements, from contouring quickly (4.5 min) and repeatedly (six times) up to 10° deflection (opposite directions) without degradation, and rapid cooling by quenching in room temperature saline (cool-off time to room temperature: 75). In short, each of these specimens was heated from 25 to 280 °C, contoured every other cycle, and quenched to 25 °C, all in less than 6 min, and were subject to this demanding protocol 14 times with only 10 min between cycles. The material was extremely resilient: strength decreased only 3% from as-received material, strain decreased 9%, mostly in the inelastic segment of the deformation, and modulus was unchanged.

Fracture toughness decreased a minor 8%. The proportion of matrix mass that was crystalline decreased less than 3%. The fracture surface morphology showed retention of fibre-matrix bonding across almost the whole surface. The ability of this composite to retain 90–100% of its physical and mechanical properties after severe repeated thermal, mechanical and cooling demands, is convincing evidence of this material's suitability for applications where contourability and fast processing is required. In addition, the unchanged crystallinity is direct physical evidence that operating room quenching in saline does not prevent crystallization of the matrix, a concern based on studies demonstrating decreased crystallinity under fast cooling protocols [13, 14].

The following experiment validated the DSC method as sensitive to crystallinity changes of CFR PEEK. Two specimens were heated to above 320 °C core temperature. This resulted in material flow at the centre-heated site and allowing the specimens to be bent into a 90° angle with a pair of pliers. These conditions indicated a substantial melting of PEEK crystals. Samples were sectioned to act as a positive control to demonstrate DSC sensitivity to changes in crystallinity. A 15–20% increase in fraction of matrix which was crystalline was observed, demonstrating that the sensitivity of DSC to PEEK crystallinity demonstrated elsewhere [12, 13] applies to this study. This supports the conclusion that samples from the other specimen groups did not show altered crystallinity.

Another approach taken to analyse the flexural data was to determine the amount of elastic and inelastic strain of the specimens. This was accomplished by constructing a 95% secant line to the modulus of each force–displacement trace recorded. A dividing line between elastic and inealastic strain was constructed to determine if the elastic behaviour of the material was affected by processing. Based on 39 specimens broken both in preliminary testing and from the CONTROL, 0S, 0RT, 10RT and 10RQ groups, it was observed that the material demonstrated an elastic strain of 1.30% (0.11), varying over only a -11% to $+6\%$ range after any treatment in this study or in preliminary work.

The analysis of elastic–inelastic strain fraction revealed several interesting features. First of all, the uncorrected elastic strain for all specimens in one- and two-sided heating protocols was nearly the same. The values ranged from 1.18% strain to 1.40% strain for all specimen groups about a control value of 1.315% strain. Upon averaging the elastic strain for all 39 tested specimens, the average value was $1.30 \pm 0.11\%$ strain, extremely close to the $1.315 \pm 0.08\%$ strain value for the 10 unprocessed controls. In addition, an ANOVA run on all specimen groups' mean elastic strains revealed no statistically significant differences between any two groups' mean elastic strains at an $\alpha = 0.05$. This lends support to the possibility that elastic strain may not be significantly affected by any of the heating, contouring and cooling protocols used in this study. It may be a intrinsic material property within the ranges of conditions tested in this study.

The importance of this observation is that the strain-to-failure of cortical bone is very similar to the elastic strain limit observed here for 30% SCFR PEEK. This raises the exciting possibility that a permanent CFR PEEK fracture plate attached to a cortical bone would never be strained past its elastic limit once the bone had healed. The healthy bone would fracture before the plate began non-elastic deformation. In this scenario, the CFR PEEK plate would suffer no mechanical damage from inelastic loading, drastically increasing its lifetime and eliminating the need for removal due to failure.

5. Conclusions

This study was undertaken to research the concept of a thermoductile thermoplastic composite, an injection-moulded 30% short PAN carbon-fibre-reinforced polyetheretherketone, or 30% SCFR PEEK. Previous work by Brown *et al.* [5] demonstrated that this material could be contoured to 6° deflection without degradation by heating it in an electric oven at 250 °C. This study delved further into the high-temperature contourability of 30% SCFR PEEK by developing an infrared heating method into a well-documented and consistent protocol for heating 30% SCFR PEEK to temperatures suitable for contouring. Five specimen groups were tested using four techniques to check for changes in the 30% SCFR PEEK resulting from various processing operations. An analysis of the results of the processing and material evaluation concludes that 30% SCFR PEEK does not lose strength, strain to failure, stiffness, fracture toughness, crystallinity or fibre-matrix wetout as the result of heating to a 280 °C core temperature for prolonged times, contouring repeatedly in opposite directions to 10° deflection, or quench cooling at core cooling rates of up to $700\,^{\circ}\mathrm{C\,min^{-1}}$. The thermoductility of the thermoplastic composite 30% SCFR PEEK demonstrates the great promise of the concept of using thermoformable fibre-reinforced composites for structural applications, especially in the area of the fixation of skeletal fractures.

Acknowledgements

This study was funded in part by a grant from AcroMed, Inc., Cleveland OH.

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Received 7 January
and accepted 22 January 1991