Fracture resistance and failure modes of CEREC endo-crowns and conventional post and core-supported CEREC crowns

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Background/purpose: The purpose of this in vitro study was to compare the fracture resistance and failure modes of CEREC endo-crowns with the CEREC classic designed crown supported with glass fiber-reinforced composite posts and composite cores. The influences of thermal cycling and fatigue loading on both types of restorations were also investigated.

Materials and methods: Twenty extracted intact maxillary premolars were randomly divided into two groups (C and E). The crown portion of the specimens was removed to 1.5 mm above the cementoenamel junction (CEJ). All specimens were endodontically treated with a nickel-titanium rotary system and obturated with gutta-percha by a vertical compaction technique. In group C (n=10), teeth were restored with glass fiber-reinforced composite posts and composite cores with a 1.0-mm wide circumferential shoulder margin at the CEJ and a 1.5-mm ferrule. In group E (n=10), teeth were prepared for fabrication of CEREC endo-crowns. Both types of ceramic crowns were produced from ProCAD ceramic blocks utilizing a CEREC 3D CAD-CAM unit, and these were bonded to the preparations with an adhesive system and composite resin cement. Teeth were thermally cycled (2000 cycles of 5ºC/55ºC with a dwell time of 30 seconds,) and fatigue loaded (20,000 cycles at 5 kg and 3 Hz) in a custom-made fatigue simulator. All specimens were loaded in a universal testing machine with a cross-head speed of 0.5 mm/s until fracture occurred. Fracture resistance and failure modes were statistically evaluated with a t test and χ² test.

Results: The mean fracture resistance ± standard deviation was recorded as follows: 1163.30±163.15 N for group C and 1446.68±200.34 N for group E. A significant difference was found between groups with respect to fracture resistance (P<0.05). Regarding failure modes, most specimens of both groups exhibited unfavorable fractures, and no significant difference was found between the two groups.

Conclusion: The bonded ceramic endo-crowns showed a significantly higher fracture resistance than the classic reinforced and designed group and, therefore, offer a feasible alternative for severely damaged teeth.
Introduction

The rehabilitation of severely damaged coronal hard tissue and endodontically treated teeth is always a challenge in reconstructive dentistry. Clinical concepts regarding the restoration of non-vital teeth are controversial and are based on profuse and inconclusive empirical literature. The primary reason for reduction in stiffness and fracture resistance of endodontically treated teeth is the loss of structural integrity associated with caries, trauma, and extensive cavity preparation, rather than dehydration or physical changes in the dentin.\(^1\) Reduction of the tooth architecture results in increased cuspal deflection during loading (either continuous or cyclic) and delayed cuspal recovery following removal of the load.\(^5\) Therefore, the loss of structural integrity increases the occurrence of crown fractures and microleakage at the margins of restorations in endodontically treated teeth compared with “vital” teeth.\(^4,8\) Additionally, the lack of vitality greatly restrains the sensory feedback during peak loads and results in non-vital teeth being more prone to fracture.

The classical approach for restoring endodontically treated teeth is to build up the tooth with a post and core, which have physical properties close to those of natural dentin, utilizing adhesive procedures and placement of full-coverage crowns with a sufficient ferrule.\(^9\) An ferrule with 1 mm of vertical height was shown to double the resistance to fracture versus teeth restored without a ferrule.\(^12\) Another study showed that a ferrule with 1.5–2 mm of vertical tooth structure has maximum beneficial effects and more favorable fracture patterns.\(^13\) With this understanding, additional treatments such as surgical crown lengthening or orthodontic tooth extrusion are recommended if the minimal ferrule effect cannot be obtained.\(^1,14\) Additionally, a significantly lower static failure load occurs after crown lengthening is accomplished.\(^15\) Preparation of a post space also increases the risk of accidental root perforation.

With recent developments of adhesive techniques and ceramic materials, the advantage of adhesive restorations is that a macroretentive design is no longer a prerequisite if there are sufficient tooth surfaces for bonding. With the adhesive technique, creating a ferrule is a drawback because of loss of the natural tooth structure and enamel. Minimally invasive preparations to preserve a maximum amount of tooth structure are considered the gold standard for restoring teeth. Endo-crowns strictly follow this rationale owing to a decay-orientated design concept. This type of preparation consists of a circumferential 1.0–1.2-mm butt margin and a central retention cavity inside the pulp chamber, and constructs both the crown and core as a single-unit, i.e., a “monobloc”.\(^16,17\) The monobloc foundation of this technique utilizes the available surface in the pulp chamber to obtain stability and retention of the restoration through adhesive bonding. Moreover, dental computer-aided design/computer-aided manufacturing (CAD-CAM) systems realize the possibility of chair-side design and automatic production of these single-unit ceramic restorations.

In vitro studies reported that bonded endo-crowns showed comparable fracture load values compared with conventional crowns.\(^18,19\) Several clinical case reports showed the potential of this restorative approach to provide adequate function and esthetics, even with compromised tooth integrity of non-vital molars.\(^17,20–24\) Two techniques were demonstrated for the production of all-ceramic endo-crowns: the single-visit CEREC 3D (Sirona Dental Systems, Bensheim, Germany) CAD-CAM technique and the Empress II (Ivoclar Vivadent, Schaan, Liechtenstein) pressed ceramic technique. Bindl and Mörmann\(^16\) reported that 19 adhesively bonded CEREC endo-crowns (4 premolars and 15 molars) in 13 patients functioned satisfactorily for over 28 months, and the only molar endo-crown which failed was because of recurrent caries. The overall clinical quality of CEREC endo-crowns was good, and the clinical concepts appeared feasible. However, the samples used in most of those clinical cases were molars or incisors.

Salis et al.\(^25\) described a higher prevalence of fractured maxillary premolars compared with mandibular premolars. In the maxilla, 49% of fractures occurred in premolars, of which half involved the functional cusp. Maxillary premolars are usually bulkier than the anterior teeth, but are often single-rooted teeth. The height of the cusps is more highly related to the area of the base. Consequently, they are more likely to be subjected to lateral forces during mastication than molars because of the steep cuspal incline. Therefore, all of these factors make maxillary premolars prone to fracture after restoration.

Clinically, the accumulation of microstructural damage during mastication, which is enhanced in an aqueous environment,\(^26\) may induce catastrophic failure, while prior cyclic loading significantly decreases the fracture strength of all-ceramic crowns.\(^27\) Since fatigue loading and thermal cycling are important factors in regard to the clinical performance of restorations, their influences on both types of restorations were also investigated in the present study.

This in vitro study examined the fracture resistance and fracture modes after thermal cycling and fatigue loading of CEREC endo-crowns and classically constructed CEREC ceramic crowns with glass fiber-reinforced composite posts in extensively...
damaged and endodontically treated maxillary premolars. The hypotheses of this study were as follows:
1. There is no difference between the mean fracture resistance of teeth restored with CEREC endo-crowns and that of teeth restored with classic CEREC ceramic crowns with a glass fiber-reinforced composite resin post and composite resin core.
2. Endo-crowns have more favorable fracture properties than conventional post and core-supported CEREC crowns.

Materials and methods

Twenty intact, non-carious, human maxillary premolars without cracks, extracted for orthodontic reasons, were cleaned and stored at 18°C in normal saline and randomly assigned to two groups of 10 teeth each. Teeth of similar size and shape were selected by root length and crown dimensions after measuring the buccolingual and mesiodistal widths at the cementoenamel junction (CEJ) in millimeters, and allowing a maximum deviation of 10% from the mean. The crown portion of all premolars was removed to within 1.5 mm above the CEJ and endodontically treated with ProTaper nickel-titanium (Ni-Ti) rotary files, a 16:1 contra angle handpiece, and ATR Teknica Vision Motor (Dentsply Maillefer, Ballaigues, Switzerland) according to the manufacturer’s instructions, and was obturated with gutta-percha by a vertical compaction technique. Specimens were restored with classic CEREC all-ceramic crowns in group C, while teeth were restored with CEREC endo-crowns in group E (Fig. 1).

In group E, the “endo” preparation consisted of a circular butt margin with a depth of the central retention cavity of 5 mm from the cavosurface margin with rounded internal line angles. In group C, all specimens were prepared with a 1.0-mm-wide circumferential butt margin at the CEJ and a 1.5-mm ferrule. The standardized depth was verified using a scaled periodontal probe (instrument number 23/UNC 15; Hu-Friedy, Chicago, IL, USA). All preparations were made by means of a number 56 high-speed bur (60018; Midwest, Des Plaines, IL, USA) with water coolant; the bur was replaced every five preparations. In group C, tapered glass fiber-reinforced composite posts (Premier Anatomic IP-110-VR; Innotech, Robbio, Pavia, Italy) were identically adhesively cemented to teeth with All-Bond 1 and C & B Cement (Bisco, Schaumburg, IL, USA) according to the manufacturer’s instructions, leaving a 5-mm apical gutta-percha seal, and a built up composite resin core (A2, Filtek Z250; 3M ESPE, Seefeld, Germany).

Both the ceramic endo-crowns (group E) and conventional ceramic crowns (group C) were designed using the CEREC 3D CAD-CAM unit (Sirona Dental Systems) and machined from ProCAD leucite-reinforced ceramic blocks (200, 114; Ivoclar Vivadent). CEREC software version 3.01 (Sirona Dental Systems) and the “crown/correlation” mode were used for the construction of the experimental crowns. The all-ceramic crowns were fitted and polished using CeramiPro Dialite polishing discs (L260DBC, L260 DRM and L260GXF; Brasseler, Savannah, GA, USA).

Before insertion, the intaglio surfaces of the ceramic crowns were etched with hydrofluoric acid (Ultradent Porcelain Etch, 9%; Ultradent Products, South Jordan, UT, USA) for 60 seconds, then rinsed for 60 seconds with running water and dried for 30 seconds with oil-free air. A silane-coupling agent (Monobond S; Ivoclar Vivadent) was applied and allowed to dry for 1 minute. The abutments were etched with 37% phosphoric acid-etching gel (Ultra Etch; Ultradent Products) for 40 seconds, rinsed for 30 seconds, and dried with oil-free air for another 20 seconds. The adhesive system (Syntac Classic; Ivoclar Vivadent) was applied to the preparations according to the manufacturer’s instructions.

All crowns were adhesively luted with Variolink II luting composite resin cement (low viscosity; Ivoclar Vivadent). The Variolink II base and catalyst were mixed at a 1:1 ratio and coated onto the inner surface of the crowns. Crowns were seated with light finger pressure, and excess luting material was removed. The light-polymerizing unit (Bluephase; Ivoclar Vivadent) was held on the buccal, mesial, lingual, distal and occlusal surfaces for 1 minute. The curing power was 1200 mW/cm². The curing mode was initiated with a soft start for 30 seconds, followed by high-power mode for 30 seconds. Before testing, each tooth was vertically mounted in self-cured acrylic resin (Truetime Industrial, Tainan, Taiwan) in customized stainless steel mounting rings for the thermal cycling, fatigue loading, and load-to-failure test. The crowns of the teeth remained free of the acrylic, and the root was covered to a height 2 mm below the CEJ (which is approximately the level of alveolar bone in a healthy tooth). The rings were removed following the mounting procedure. All specimens were stored in saline at room temperature for 24 hours before testing.

Specimens were subjected to thermocycling at 5°C for 30 seconds and at 55°C for 30 seconds for 2000 cycles in a thermal cycling machine (custom made; Chang Gung University, Taoyuan, Taiwan).

According to a study by Chen et al.27, the rapid rate of decline in strength of a ceramic restoration leveled off after 10,000 cycles of dynamic loading. Hence, all specimens were prior fatigue-loaded
Fracture resistance of endo-crowns

Fracture resistance of endo-crowns with 5 kg/cm² at 3 Hz for 20,000 cycles in the fatigue simulator (custom made; Chang Gung University). Steel spheres (5.00-mm radius of curvature), the same as those used in the load-to-failure test, were used as antagonists against the test crowns and were loaded cyclically at the same area of the crowns as in the universal testing machine. Each specimen was identically positioned in a metal holder so that the steel sphere simultaneously contacted the two cuspal inclines and was loaded along the long axis of the specimen (Fig. 2). For the load-to-failure test, 20 crowns from both groups were loaded in the universal testing machine with a cross-head speed of 0.5 mm/s until fracture occurred.

The fracture resistance was recorded in newtons, and the failure modes of all samples were assessed from periapical radiographs after fracture by two observers. “Favorable failures” were defined as repairable failures above the level of bone simulation and included adhesive failures. On the contrary, “unfavorable failures” were defined as non-repairable, catastrophic failures below the level of bone simulation, including vertical root fractures.²⁸ The fracture resistance was evaluated by t test statistics, and a χ² test was used to compare the failure modes of specimens. The level of significance was set at P < 0.05.

Results

The mean, median, standard deviation, and minimum and maximum fracture resistances are shown in Table 1. Group E revealed a higher mean fracture resistance (1446.68 ± 200.34 N) than that of group C (1163.30 ± 163.15 N), and the independent t test revealed a statistically significant difference between the mean fracture resistance of the two groups (P = 0.0039). All tooth specimens of both groups fractured in a direction continuous with the fracture line of the crown. The failure modes are shown in Table 2. Most of the failure modes in both groups were unfavorable (65%). The majority of the failure modes (55%) consisted of an oblique shearing of the buccal cusp from the occlusal fissure to the buccal coronal third of the root area. One classic ceramic crown lost adhesion of the resin to the dentin and completely broke. A crack line in a

Fig. 1 Scheme of tooth preparation of the experimental teeth. (A) Group E: “endo” preparation. (B) Group C: classic preparation. CEJ = cementoenamel junction.

Fig. 2 Position of the specimen in the setup for cycling and static loading.
mesiodistal direction was observed on another abutment. The \( \chi^2 \) test demonstrated no significant difference in the frequencies of favorable and unfavorable failure modes between the two groups (\( P = 0.639 \)).

**Discussion**

This *in vitro* study simulated the “compromised biomechanical condition” of severely damaged and endodontically treated maxillary premolars. The classical treatment option is a custom-made casting post-and-core covered by metal or porcelain fused to a metal crown with a sufficient ferrule. However, Gegauff\(^1^5\) reported that surgical crown lengthening to create a ferrule demonstrated a significantly lower static failure load because of the decrease in the cross section of the preparation combined with an altered crown-to-root ratio. Creating a sufficient ferrule might cause the loss of sound tooth structure and result in compromised bonding strength, because enamel is preferred to dentin for bonding.\(^2^9\),\(^3^0\)

In the present study, creating a sufficient ferrule might have been one of the reasons that the classic crown had a lower fracture resistance than the endo-crowns.

The thickness of the ceramic occlusal portion of endo-crowns is usually 3–7 mm. An *in vitro* study showed that the fracture resistance of ceramic crowns increases with increasing occlusal thickness.\(^3^1\) Mörmann et al.\(^1^8\) also reported that the fracture resistance of endo-crowns with an occlusal thickness of 5.5 mm was two times higher than that of ceramic crowns with a classic preparation and an occlusal thickness of 1.5 mm. In this study, the higher fracture resistance of adhesively bonded ceramic endo-crowns corresponded with those previous reports.

Clinically, the normal biting force is 222–445 N for the maxillary premolar area,\(^3^2\) and the occlusal force was observed to be as high as 520–800 N during clenching.\(^3^3\) It was also reported that intact maxillary premolars fractured at a load of approximately 1121–1124.6 N.\(^8\),\(^3^4\) This study showed that the fracture resistance of endo-crowns was greater than that of intact premolars, and the endo-crown design could restore the structural integrity and the strength of an endodontically treated and severely decayed tooth. However, Bindl et al.\(^3^5\) reported that the survival rate of CEREC endo-crowns over 55 months was comparable to classically constructed crowns on molars (87.1%), but was inadequate for premolar crowns (68.8%). It is noteworthy that all of the failures of endo-crowns on premolars in that study were caused by loss of adhesion. Loss of adhesion of endo-crowns on premolars may have been because the surface for adhesive bonding was smaller, and the greater ratio of the prepared tooth structure to the overall crown and cusp height resulted in higher leverage on the premolars than molars. Salis et al.\(^2^5\) also described that premolars with deep occlusal fissures are more flexible than those with shallow or no fissures. Therefore, the morphologic design of the endo-crown on maxillary premolars should have a flatter occlusal table to reduce the height of the crown and the cuspal inclines resulting in shallower fissures to reduce cuspal deflection and the risk of fracture during mastication.

The use of human teeth as abutment material in this study might have increased the variability of the fracture load compared with artificial manufactured abutments. Additional variable factors which must be considered are the tooth anatomy, abutment retention after manual preparation, and the character of the surface structure for bonding. In spite of these variables, the use of human teeth as the abutment material more closely approximates a clinical situation with respect to tooth architecture and morphology. Furthermore, the dentin and enamel surface for bonding, the contour of the pulp

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**Table 1. Fracture strength (in newtons) of the two groups**

<table>
<thead>
<tr>
<th>Fracture strength (N)</th>
<th>Group E (( n=10 ))</th>
<th>Group C (( n=10 ))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>1446.68*</td>
<td>1163.30*</td>
</tr>
<tr>
<td>Median</td>
<td>1472.18</td>
<td>1110.61</td>
</tr>
<tr>
<td>Standard deviation</td>
<td>200.34</td>
<td>163.15</td>
</tr>
<tr>
<td>Maximum</td>
<td>1745.42</td>
<td>1408.20</td>
</tr>
<tr>
<td>Minimum</td>
<td>1120.00</td>
<td>1000.50</td>
</tr>
</tbody>
</table>

*Fracture loads significant differed, \( P = 0.0039 \) (t test). Standard deviation Group E = group with endo-crowns; Group C = group with classic all-ceramic crowns.

**Table 2. Frequencies of different fracture modes in the two groups**

<table>
<thead>
<tr>
<th></th>
<th>Group E* (( n=10 ))</th>
<th>Group C* (( n=10 ))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unfavorable</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Buccal cusp</td>
<td>5</td>
<td>4</td>
</tr>
<tr>
<td>Palatal cusp</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Both cusps</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Favorable</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Buccal cusp</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Palatal cusp</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Both cusps</td>
<td></td>
<td>1</td>
</tr>
</tbody>
</table>

*Fracture modes did not significant differ, \( P = 0.6392 \) (\( \chi^2 \) test). Group E = group with endo-crowns; Group C = group with classic all-ceramic crowns.
chamber and root canals for post placement, and the ratio between the crown and root are more accurate than on an artificial resin tooth. At the same time, the selection of teeth of similar sizes and shapes was performed before testing to minimize possible variations and errors.

In this study, the lack of a simulated periodontal ligament was permissible, because it was expected that with single crowns, there is practically no difference in the fracture resistance between teeth with and without this shock absorbing layer around roots under a static loading test. Furthermore, our experience with artificial silicone periodontium around the roots of abutment teeth showed that the thickness of the silicone layers is more than that in clinical situations. Moreover, a non-standardized artificial silicone periodontium might cause uncontrolled mobility of abutment teeth and more errors. In spite of the conformity of the strength of the restored teeth, the fracture patterns of static loading and rigidly mounted teeth might be atypical of those found clinically. The slow loading rate of static loading did not simulate the clinical situation in which tooth fractures occur quickly and accidentally.

Most of the failure modes of both groups in the present study were unfavorable (65%), and the majority of failure modes (55%) were an oblique shearing of the buccal cusp from the occlusal fissure to the buccal coronal third of the root. The fracture path for maxillary premolars in the present study was similar to that of intact maxillary premolars receiving repeated rapid impacts as reported by Salis and colleagues. Most of the fractures involving the root imply that a significant amount of force was transmitted to the root. Consequently, when fractures are so severe, extensive surgical crown lengthening is often required. From this aspect, extraction might be a more suitable treatment option.

Stress distribution and initiation of fracture were not specifically examined in this study. According to the failure modes in the present study, the major stress concentration was at the base of the occlusal fissure. This finding is in accord with a report by Salis and coworkers. Zarone et al. reported that the stress concentration in maxillary central incisors restored with an endo-crown is at the interface according to a three-dimensional finite element analysis. The interfaces of materials with different elastic moduli result in a weak point of a restorative system, because the stiffness mismatch of different materials influences the stress distribution. Differences in the elastic moduli among ceramic, luting cement and the dentin might pose a risk of root fracture. Newly developed materials with mechanical properties as similar as possible to those of natural tooth hard tissues may decrease the frequency of unfavorable root fractures.

The loading position and loading angle relative to the post site in group C may have influenced the fracture modes, because tensile stresses at the adhesive interfaces among the glass fiber-reinforced composite post, the composite resin core, and the ceramic crown would weaken the structure. Using an endo-crown restoration presents an advantage of reducing the effect of multiple interfaces in the restorative system and thereby makes the experimental tooth more similar to a monobloc.

In considering the effect of loading cycles, DeLong et al. and Sakaguchi et al. reported that amalgam and composite material wear produced after 240,000 to 250,000 masticatory cycles in a chewing simulator corresponded to the wear measured after 1 year of clinical service. Therefore, in most laboratory studies, 1,200,000 cycles are used to simulate a service time of 5 years. According to another study, the fracture load of Vita Mark II crowns showed a decrease with increasing load cycles, and the rapid rate of decline in fracture strength leveled off after 10,000 cycles of loading. However, these correlations may only be related to the specific materials tested with specific parameters, so they cannot be generalized too widely. In the present study, the fatigue test was only run for 20,000 cycles to reduce operation and evaluation time. None of the ProCAD crowns subjected to this amount of cyclic loading demonstrated any evidence of cracking. Perhaps a higher number of fatigue cycles would have produced different results, with evidence of cracks during dynamic loading and lower fracture load values.

The development of in-office CAD-CAM systems and software offers several advantages in clinical practice. First, with the change in the grinding system from discs to a stepped cylindrical diamond bur and a cylindrical diamond with a tapered tip, the more-flexible CAD-CAM shaping technique allows custom shaping and more precise milling of ceramic crowns. Furthermore, the adaptation of the inner surface of a restoration and the replication of the occlusal morphology are better. Second, endo-crowns can be produced and seated in one appointment. Third, this method saves time and reduces expenses associated with a build-up procedure of the post and core. Despite these advantages, there are clinical problems with the depth of the optical impression to record the crown, pulp chamber, and part of the canal. According to a study by Mörmann and Bindl, the depth scale of the intraoral scanning camera is limited to a single value of 6.4mm with CEREC 2. Even with the time-consuming effort required for software-supported adjustments, the optical depth of field is 14mm. The limited optical depth of field might result in a blurred image of the central retention cavity of the endo preparation if
adjacent teeth limit the position of the camera head. With improvements in the intraoral three-dimensional scanning camera of the CEREC 3D unit, the depth scale is extended to about 20mm through “double triangulation”. Extended depth of field through double triangulation, thereby, overcomes this limitation.39

According to the results of the present study, the first hypothesis was accepted, and the fracture resistance of CEREC endo-crowns was better than that of classic crowns. The second hypothesis was rejected, since there was no significant difference in the failure modes between the two groups.

In summary, endo-crowns provide an alternative to conventional treatment of severely compromised posterior teeth, especially in situations such as a flared root canal, inadequate clinical crown length, and insufficient interocclusal space. According to the present study, endo-crowns should be considered a feasible, conservative and esthetic restorative approach. These adhesive monobloc restorations preserve the maximum tooth structure, reduce the need for a macrorepetitive geometry, and provide more efficient and better esthetic results than metal or porcelain fused to metal crowns. Despite the suggestion by Pissis17 that there must be a 3-mm diameter cylindrical pivot and 5-mm depth for the first maxillary premolars and at least 5-mm diameter and 5-mm depth for molars, the precise dimensions of the central retention cavity of the endo preparation are not clearly determined. Further prospective in vitro and in vivo studies to evaluate the determinative factors and dimensions of the central retention cavity and clinical studies to test the longevity of endo-crowns as a single prosthesis and abutment of fixed partial dentures are necessary.

Acknowledgments

The authors greatly thank Mr Yu-Wen Chang, technician of the Department of General Dentistry, Chang Gung Memorial Hospital, Tao-Yuan, Taiwan, for his kind assistance in designing and fabricating the CEREC crowns. Assistance with material testing from Dr Chun-Li Lin and Mr Chih-Chao Yang, Department of Mechanical Engineering, Chang Gung University, Taoyuan, Taiwan, is also highly appreciated.

References