# OPEN HOLE AND COMPRESSION AFTER IMPACT TESTING OF CARBON FIBRE/EPOXY LAMINATES AND THE INFLUENCE OF ENVIRONMENTAL EXPOSURE

Katleen A. M. Vallons[1], Takuya Karaki[2], Ichiro Taketa[3], Stepan V. Lomov[1], Ignaas Verpoest[1]

[1] KU Leuven, dept. Materials Engineering, Kasteelpark Arenberg 44, 3001 Heverlee, Belgium
katleen.vallons@mtm.kuleuven.be, stepan.lomov@mtm.kuleuven.be,
ignaas.verpoest@mtm.kuleuven.be

[2] Toray Carbon fibers Europe, Route de Lagor, Bassin de Lacq, Ple 4, 64150 Abidos, France
takuya.karaki@toray-cfe.com

[3] Toray Industries, Inc. Ehime-plant, Composite materials research laboratories, 1515, Tsutsui, Masaki-cho, Iyogun, 791-3193 Ehime, Japan
ichiro_taketa@nts.toray.co.jp

**Keywords:** open hole tension, open hole compression, compression after impact, fatigue

**Abstract**
The presented work contains the results of a mechanical investigation of two types of prepreg laminates. The behaviour in open hole tension, open hole compression, and compression after impact loading is investigated. Preliminary observations of the development of damage under dynamic loading are discussed, as well as the influence of exposing the test samples to various environmental conditions prior to testing.environmental conditions prior to testing.

## 1. Introduction

Results for open hole tension or compression tests and compression after impact tests on composite laminates are only occasionally reported in scientific literature, despite their large relevance for industrial applications. This study contains results on tensile and compressive open hole tests and compression after impact tests, both static and in fatigue, as well as results for tests done on samples exposed to environmental conditioning.

## 2. Materials and methods

The samples for the tests in this study were provided by Toray Industries. A quasi-isotropic stacking sequence was used for all laminates. Two types of carbon fibre – epoxy prepregs were used: T800S/3911 (further referred to as type A) and T800S/3900-2B (further referred to as type B).

Open hole tension (OHT) tests were done in accordance with ASTM D5766. The test sample dimensions were 38*305mm with a thickness of 2.1 mm for type A and 1.55 mm for type B (8 ply quasi-isotropic lay-up). A central hole with diameter 6.35mm was carefully drilled in the samples.

ASTM standard D7648 was followed for the open hole compression (OHC) tests, using a special anti-buckling rig. The test sample dimensions were the same as for the OHT tests, except for the thickness: 4.2 mm for type A and 3.1mm for type B (16-ply quasi-isotropic lay-up).

Excerpt from ISBN 978-3-00-053387-7

Compression after impact (CAI) tests were done on samples with a thickness of 4.2 mm (type A, 16 plies) and 4.6 mm (type B, 24 plies). Sample dimensions were 152*102 mm. Testing standard ASTM D7137 was used for these tests. Each CAI sample was impacted by a drop-weight impact of 6.7 J/mm thickness, i.e. 28.2 J for type A and 30.7 J for type B. The impact damage was measured by ultrasonic C-scan prior to the compression tests. The OHT, OHC and CAI tests were all done both in static mode and in fatigue mode.

The static tests were repeated on samples that had previously been subject to environmental conditioning. Four types of conditioning were used (see figure 1): (1) thermal exposure (TE); (2) moisture exposure (ME); (3) thermal cycle exposure (TCE); (4) hygrothermal cycle exposure (HTE).

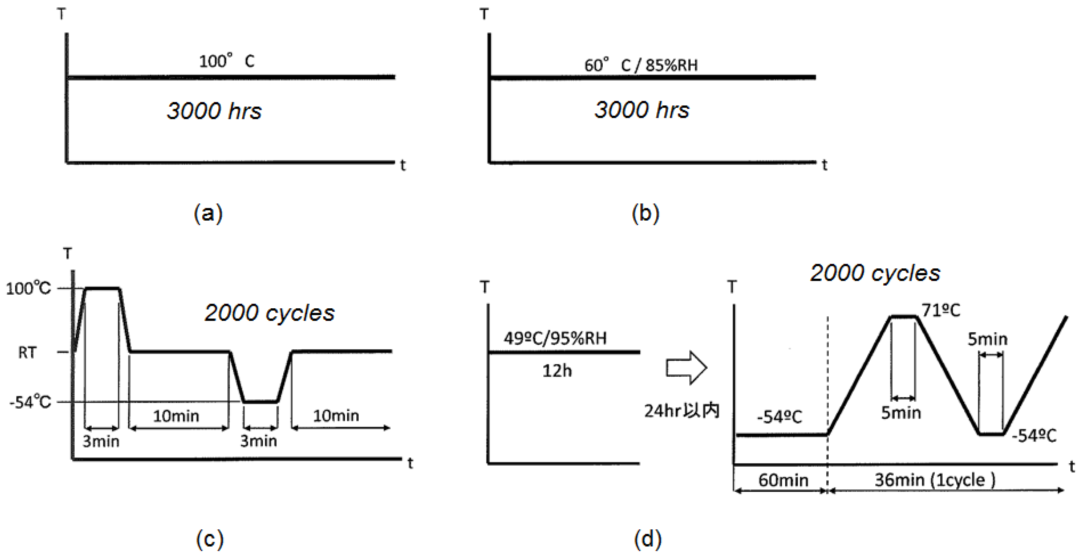



**Figure 1.** Environmental conditioning parameters. (a) thermal exposure (TE); (b) moisture exposure (ME); (c) thermal cycle exposure (TCE); (d) hygrothermal cycle exposure (HTE). [1]

## 3. Results and discussion

### 3.1 Open hole tension

No difference was noted between the open hole tensile strength of the two materials: 506 ± 6 MPa for Type A versus 506 ± 15 MPa for Type B. The fatigue behaviour was found to be excellent for both material types: the fatigue life curve is very flat (see figure 2), with no failures prior to one million cycles for stress levels below 97% of the static strength. Samples tested up to one million cycles did, however, show clear signs of damage to the off-axis plies.

Excerpt from ISBN 978-3-00-053387-7

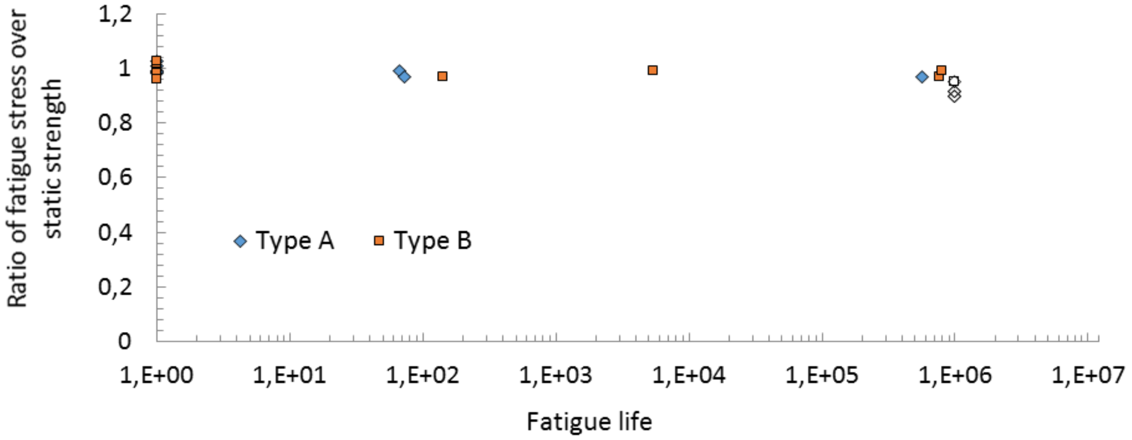



**Figure 2.** Results of the OHT fatigue tests (R=0.1, f= 5Hz). Open markers are run-out tests.

Visual observation of the damage evolution during fatigue showed that damage starts in the 90° plies early on in the tests, followed by cracking and delamination of the 45° oriented layers later on. Final failure was by explosive failure of the 0° plies.

When compared to the previously observed range of OHT strengths for unconditioned samples, no significant influence on the OHT strength was noted as a consequence of the various types of environmental exposure, for either of the materials, as illustrated in Figure 3.
It should be noted that material type A consists of layers with a larger thickness than type B. It is known that thicker layers can lead to earlier damage inducement and may lead to lower mechanical properties. In the present case, however, no such influence was noted for the OHT tests.

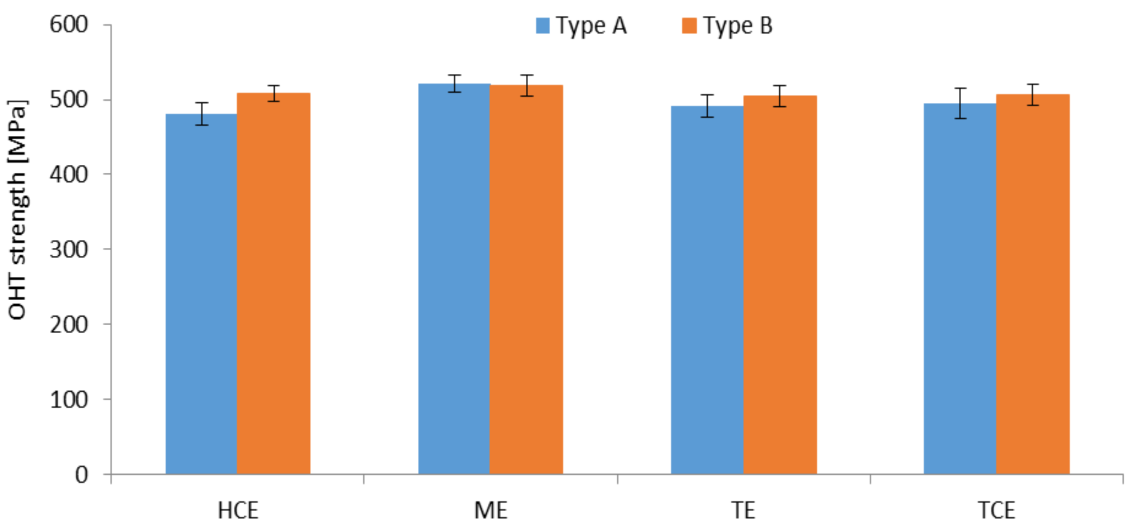



**Figure 3.** OHT strength after environmental conditioning: thermal exposure (TE), moisture exposure (ME), thermal cycle exposure (TCE), hygrothermal cycle exposure (HTE).

Excerpt from ISBN 978-3-00-053387-7

### 3.2 Open hole compression

All OHC test samples failed in the hole region by means of very localized buckling and delamination. The observed compression strength for the Type A laminate was found to be 338.2 ± 9 MPa, which is about 13 % higher than that for the type B material (300 ± 10 MPa). This is a difference of 33 % (Type A) and 41 % (Type B) compared to the open hole tension strength as described above. Also for the static OHC tests, no negative influence of the greater layer thickness of type A was found. Instead, a small positive difference was even noted.

The results of the OHC fatigue tests are graphically represented in figure 4. For the higher load fractions (ratio of maximum fatigue load over static OHC strength), the results seem to indicate a slightly lower fatigue life for the Type A material than for the Type B material, for an equal fraction of the static strength. For the lowest tested fraction of the static strength (0.75), no difference was observed.

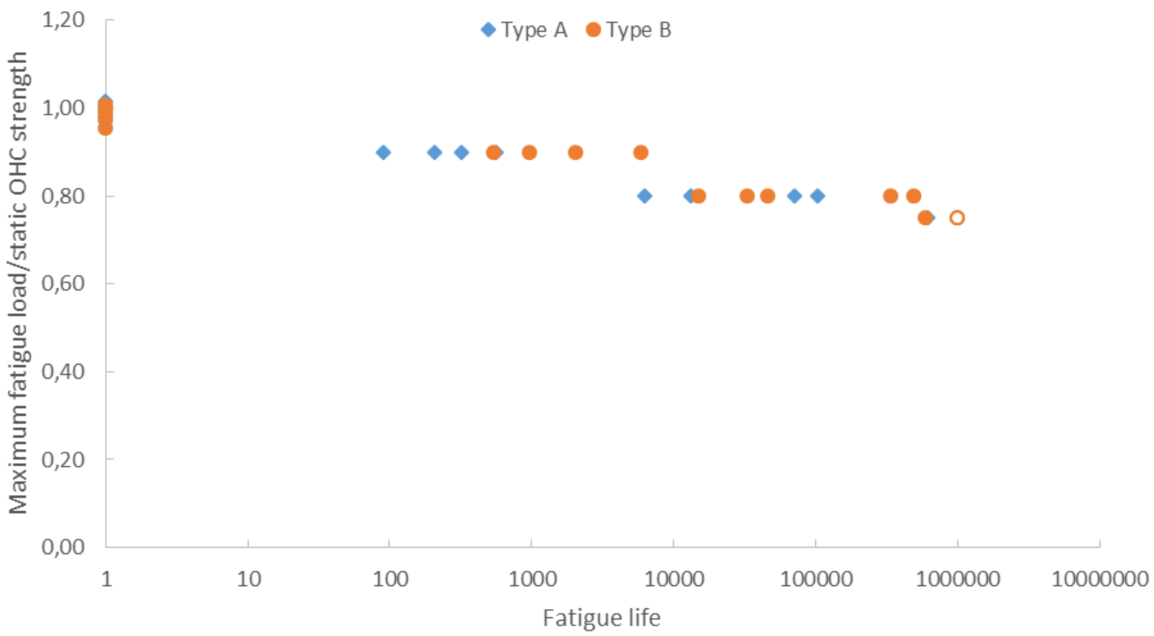
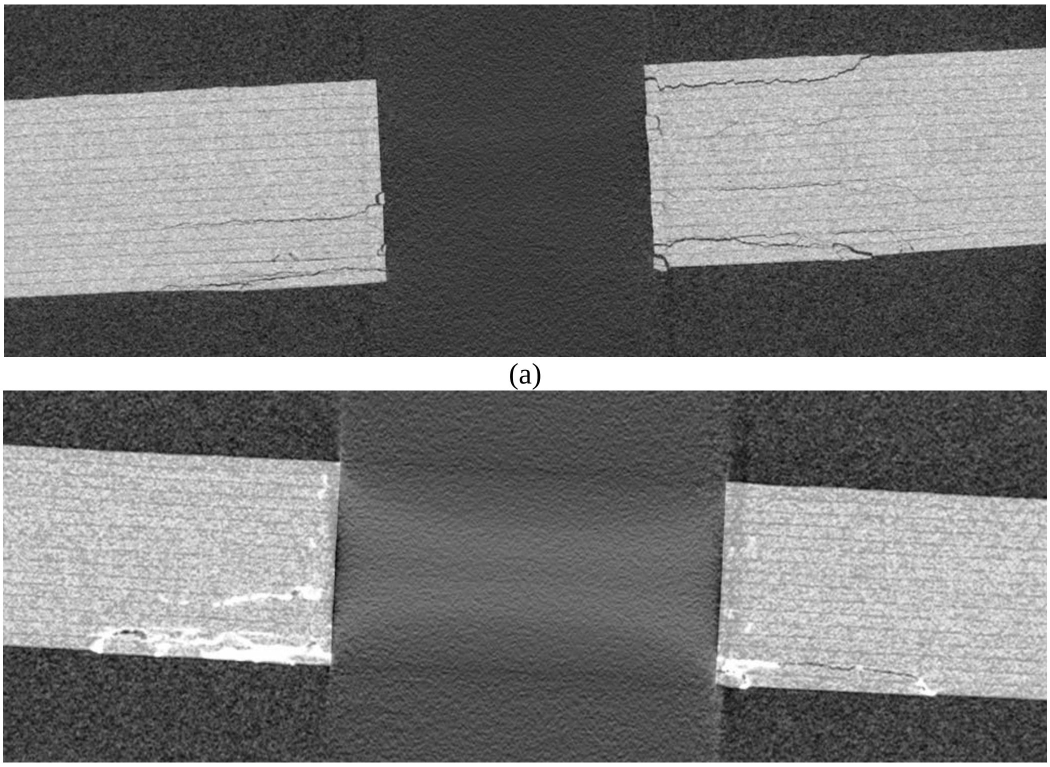



**Figure 4.** Test results of the OHC fatigue tests (R=10, f=5 Hz). Open markers are run-out tests at $10^6$ cycles.

High-resolution µ-CT observations were done on OHC fatigue samples tested up to 80% of the static tensile strength for different numbers of cycles. Examples of such a µ-CT image are shown in Figure 5. They represent a horizontal slice through the hole area of a Type A and a Type B sample close to the end of the fatigue life. The extent of damage for an equivalent number of cycles was found to be somewhat earlier and more pronounced for the type A material than for the type B material, which correlates with the slightly lower fatigue life of the former. These observations may be related to the higher thickness of the layers in material A, which could lead to earlier damage initiation and failure.

Excerpt from ISBN 978-3-00-053387-7



(a)

(b)

**Figure 5.** Micro-CT image of the damage in (a) a Type A OHC fatigue sample tested up to 8341 cycles at 80% of the static strength and (b) a type B OHC fatigue sample tested up tp 10000 cycles at 80% of the static strength (with hexabrix penetrant dye).

Figure 6 shows the OHC strength results for the environmentally exposed samples. When compared to the previously observed range of OHC strengths for unconditioned samples, no significant decrease in strength was noted as a consequence of the environmental exposure for the Type B material. For the Type A material, only a very slight decrease compared to the non-conditioned samples was noted for the moisture exposure samples. For the other conditions, no significant decrease was found.

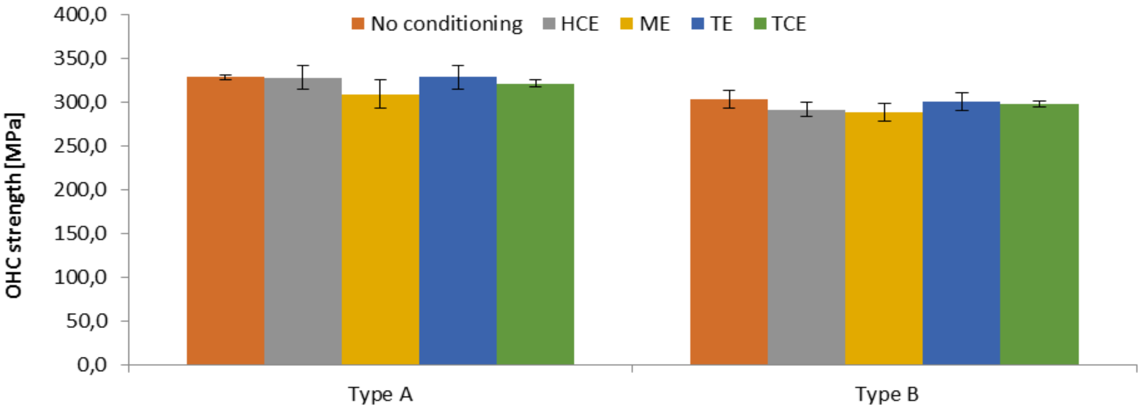



**Figure 6.** OHC strength after environmental conditioning: thermal exposure (TE), moisture exposure (ME), thermal cycle exposure (TCE), hygrothermal cycle exposure (HTE).

### 3.3 Compression after impact

Figure 7 shows the measured compression after impact strength as a function of the impact damage area as measured by ultrasonic C-scan. The measured damage area is larger for the Type A material than for the Type B material, but this may be because of the fewer plies in the former material (16 vs 24). In consequence, the average CAI strength of the Type A material is slightly lower than that of the Type B material.
For the type B material, there is no clear relation between the impact damage and the strength, but for the type A material, there is a correlation between the two: as can be expected, a larger impact damage area gives rise to a lower CAI strength.

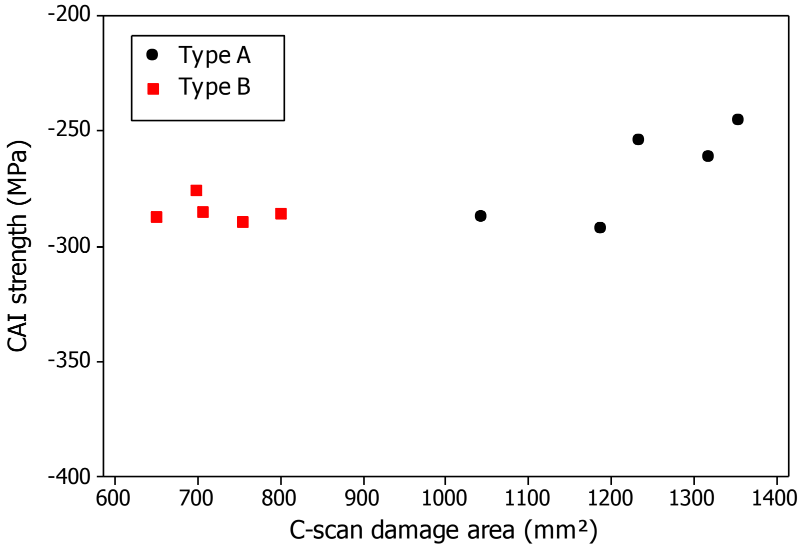



**Figure 7.** CAI strength versus impact damage area for the two materials.

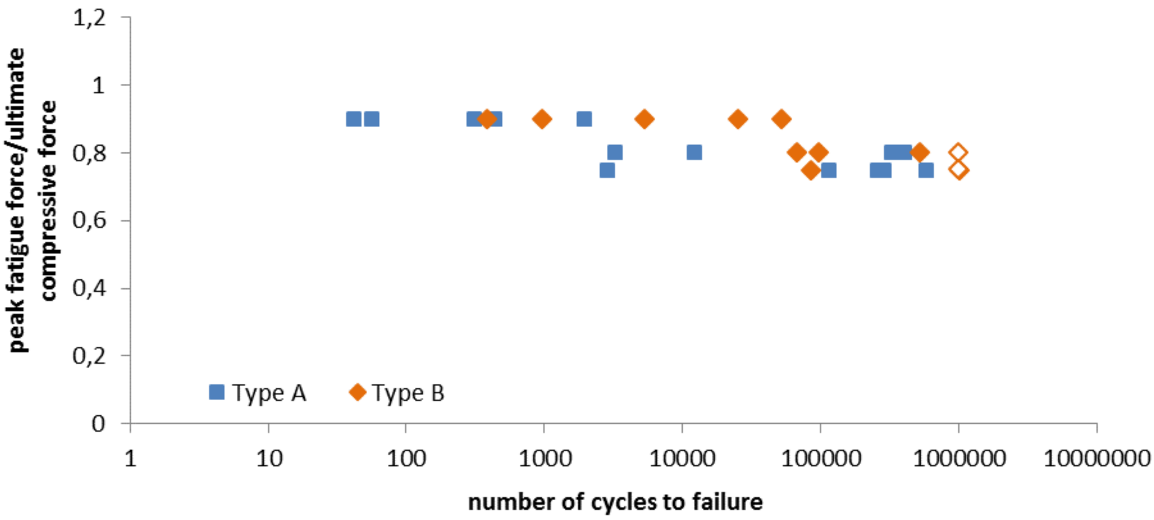



**Figure 8.** CAI fatigue test results. Open markers indicate run out tests at $10^6$ cycles.

Excerpt from ISBN 978-3-00-053387-7

The CAI fatigue life of the Type B samples was slightly longer than that of the Type A samples (see figure 8). This may again be explained by the larger size of the delamination damage in the latter samples.
Compression after impact fatigue tests at 90% of the static failure load were periodically stopped to determine the delamination size as a function of number of cycles by C-scanning. No significant growth in delamination size was noted for either material before final failure.

The static CAI tests were repeated on samples exposed to the environmental conditioning mentioned above. No significant difference in CAI strength was found between the samples with different environmental conditioning and the unconditioned ones. This means that there is no distinguishable influence of the used temperature and moisture profiles on either of the materials.

## 4. Conclusion

This paper reported on the results of a study on two types of quasi-isotropic prepreg-based laminates, investigating the behaviour under open hole tension, open hole compression and compression after impact conditions.

In general, no major differences were found between the mechanical properties of the two materials. For most of the studied properties, the type A material (T800S/3911) performs as well as the type B material (T800S/3900-2B). The open hole tension behaviour of the laminates was very similar, with no significant differences in strength or fatigue life. Open hole compression strength was higher for type A than for type B, but the fatigue life was slightly shorter for the same fraction of the static strength. In compression after impact loading, the static strength and fatigue life were somewhat higher for the type B material.

Even after long-term exposure to temperature (cycling) or moisture (cycling) or combinations thereof, no significant decrease in strength was noted for either of the three loading cases (OHT, OHC, CAI), indicating a very strong resistance to moisture and temperature degradation.

## References

[1] M. Moriyama, Kenichi Yoshioka, and Akihiko Kitano, 'Durability of Aircraft Structural Composites Processed by VaRTM', *presented at the Composite Durability Workshop (CDW-15), Kanazawa Institute Technology, Kanazawa Japan*, 2010.

*Excerpt from ISBN 978-3-00-053387-7*