Numerical Analysis and Experimental Verification of Ti/APC-2/Kevlar Hybrid Composite Laminates due to Low-Velocity Impact

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Abstract

The residual mechanical properties of Ti/APC-2/Kevlar/epoxy hybrid composite laminates after low velocity impact were investigated at room temperature. There were three types of samples tested, including three layered [Ti/$(0/90)_s$/Ti], five layered [Ti/$(0/90)_2$/$\overline{\text{Ti}}$]$_s$ and nine layered [Ti/Kevlar/Ti/$(0/90)_2$/$\overline{\text{Ti}}$]$_{s.}$ The lay-ups of APC-2 were stacked in a way of cross-ply sequence, while Ti layer was anodized with chromic acid anodic method. Ti and APC-2 were combined together to fabricate the composite laminates via hot press curing process. Kevlar layers were added to cover fiver-layer composite laminates to fabricate nine-layered composite laminates via vacuum assisted resin transfer molding.

The drop-weight tests were conducted with a hemispherical nosed projectile in 10 mm diameter. The impact loads were 5kg and 10kg according to the simulated results by ANSYS. The impact heights were increased until the samples were penetrated or the height reached the maximum height, 1.50 m, of our instrument. The static tensile tests were conducted to measure the composite laminate residual mechanical properties after the impact testing.

The results showed that the bottom Ti layer absorbed more internal energy than the top Ti layer, so that the cracks were found on the bottom Ti layer more often. The crack shape was the opening that resembling petal after the penetration. Also, the ultimate tensile strength reduced significantly after the impact, and it raised slightly after the samples fully penetrated. The initial longitudinal compliance increased with the impact height increasing and decreased after the samples penetrated. Comparing the experimental data with the numerical simulation results, we found the latter was more serious than the former. On the conservative side, the results of simulation can be adopted for applications in the case of no testing data available.

Keywords: **Titanium, APC-2, Kevlar, low-velocity, impact, tensile test.**

Introduction

Fiber metal laminates (FMLs) are hybrid composite structures constructed from thin sheets of metal alloys and plies of fiber-reinforced polymeric materials. The first FMLs, called aramid-reinforced aluminum laminates (ARALLs), were introduced in 1978 at the Faculty of Aerospace Engineering at Delft University of Technology in the Netherlands [1]. In 1990, an improved type of ARALL called glass laminate aluminum reinforced epoxy (GLARE), or ARALL with glass fibers, was successfully developed[2]. Furthermore, Lin et al. [3] developed carbon-reinforced aluminum laminates, which contain carbon fibers (CFs) rather than aramid fibers. FMLs have the advantages of metal alloys and fiber-reinforced plastic (FRP) composites. Castrodeza et al. [4] demonstrated that GLARE and ARALL possess superior fracture toughness and crack tolerance to those of their constituent alloys. Vlot [5, 6] investigated GLARE and ARALL, finding that the impact resistance of FMLs was superior to that of the studied FRP. Gunnink [7] showed that ARALL retains excellent durability even after very long exposure to highly aggressive environments. Additionally, FMLs containing various types of metal alloys and FRPs have been developed by researchers for wider application. Khalili et al. [8] studied the mechanical properties of steel–aluminum–FRP laminates. Furthermore, Zhou et al. [9] investigated the tensile behavior of Kevlar fiber-reinforced aluminum laminates. Jen et al. developed magnesium/CF/PEEK nanocomposite laminates [10] as well as titanium (Ti)/CF/PEEK nanocomposite laminates [11] and obtained their mechanical properties at elevated temperatures.

Owing to the brittleness of thermosetting matrix resulted by cross-linking, the epoxy resins and epoxy-based fiber composites are susceptible to impact damage. Thermoplastics, having greater toughness, are considered to be potential for alleviating this problem [12]. Although damage inflicted by low-velocity impact appears quite complicated, the major failure modes include only matrix cracking, delamination, and fiber breakage [13]. The delamination mode of failure is induced by matrix cracks which occur prior to other failure modes. Thus, suppression of matrix cracking will suppress delamination. It is conceivable that the use of tougher matrices will yield composites that are more resistant to impact damage.

Except for the degree of damage, the plate specimens did not differ from beam specimens in failure modes or impact tolerance properties [14], i.e., no plate size effect. The postimpact load-carrying capability of a composite laminate is of prime concern to the design engineer. After a tool-drop type accident where no damage is visible from the surface, the structure is still expected to carry the full spectrum of loading. However, it may be wrong of overestimation. In all cases the residual strength decreased as the impact velocity increased. From the results [15] the tough matrix composites may provide excellent impact resistance properties at low-impact velocities. However, beyond a certain threshold velocity, i.e., $v \geq 25$m/s, the use of tough matrix materials may result in more laminate tensile and flexural strength reduction than that of brittle matrix materials. Additionally, the PEEK composites have significantly lower contact rigidity, i.e., for a given contact force the resulting indentation in the PEEK composites would be larger, yielding a larger contact area, and, therefore, a low contact pressure. A larger contact area with lower pressure will reduce the transverse shear stress concentration and thus minimize local matrix cracking.

Anodic method is a commonly used surface treatment, however, the bonding capability of polymer composites to titanium thin plates is still a problem. In order to improve the interfacial bonding capability, Ramani et al. [16] found the chromic acid anodic method was excellent. Chromic acid anodic oxidation produced an oxide layer of thickness 40~80 nm for the 5V and 10V treatments [17]. In recent years, inorganic nanoparticles filled polymer composites have attracted attention because the filler/matrix interface in these composites might constitute a great area and influence the properties of composites at rather low filler concentration [18]. Based on above-mentioned statements we fabricated Ti/APC-2 FLMs to investigate their resistance to impact loads, measure residual mechanical properties and compare the data with the results of numerical simulation by using software LS DYNA-3D.

Specimen Fabrication

The twelve-inch wide prepregs of Carbon/PEEK (Cytec Industries Inc., USA) unidirectional plies were cut and stacked into cross-ply $[0/90]_s$ laminates. The grade 1 (H: 0.015%, O:0.18%, N:0.03%, Fe:0.2%, C:0.08%) Ti sheets, supplied by Kobe Steel Ltd (Japan), were 0.5mm thick after rolled, heated and flattened with scratch brushing. The ultimate tensile strength of Ti is 353MPa, and modulus of elasticity 109GPa.

After a series of tests, the surface treatment by chromic acid anodic method of electro-plating was found better as demonstrated by the results of tensile tests. The anodic oxide coating film was observed uniform by Scanning Electron Microscope, and the composition of coating consisting of TiO_2 by Energy-Dispersive X-ray spectroscopy.

The APC-2 prepregs were sandwiched with the Ti alloy sheets to produce Ti/APC-2 hybrid $[Ti/(0/90)_s/Ti]$ three-layered and $[Ti/(0/90)_2/\overline{Ti}]_s$ five-layered laminated composites. The hot press and modified diaphragm curing process were adopted to fabricate laminates [19]. The hybrid composite specimen was a rectangular plate of 240mm(L)×25mm(W) with thickness 1.55mm and 2.50mm. Additionally, the 4.50mm thick $[Ti/Kevlar/Ti/(0/90)_2/\overline{Ti}]_s$ nine-layered laminates were covered by Kevlar layers via vacuum assisted resin transfer molding.

An MTS-810 servohydraulic computer-controlled dynamic material testing machine was used to conduct the tensile tests after the free drop impact.

Numerical Analysis

In simulation we adopted the same samples as fabricated in our lab such as $[Ti/(0/90)_s/Ti]$, $[Ti(0/90)_2/\overline{Ti}]_s$ and $[Ti/Kevlar/Ti/(0/90)_2/\overline{Ti}]_s$ three hybrid composite laminates. The finite element analysis and ANSYS/LS-DYNA 3D software were used to simulate the impact process starting from the penetration of top layer step by step to the full penetration of bottom layer with the zero velocity left. Due to symmetry only one quarter of sample was considered. The 3D Solid 164 elements with eight nodes and nine degrees of freedom for each node were used to construct the model. The bullet was a hemispherical nosed projectile of 10 mm diameters. The assumed boundary conditions were that no displacement along the symmetry edges, totally constrained for other two free edges and a plastic cushion placed at the bottom of laminate to avoid rebounce. The failure criterion was based on the value of principal strain. Herein, the failure values of principal strains were 0.0088 for 90° Carbon fibers, 0.189 for Ti alloy and 0.08 for Kevlar fibers, respectively.

The received results would provide valuable references for the next step of impact tests.

Experimental work

The APC-2 prepregs were sandwiched with the Ti alloy sheets to produce Ti/APC-2 hybrid $[Ti/(0/90)_s/Ti]$ three-layered and $[Ti/(0/90)_2/\overline{Ti}]_s$ five-layered laminated composites. The hot press and modified diaphragm curing process were adopted to fabricate laminates [19]. The hybrid composite specimen was a rectangular plate of 240mm(L)×25mm(W) with thickness 1.55mm and 2.50mm. Additionally, the 4.50mm thick $[Ti/Kevlar/Ti/(0/90)_2/\overline{Ti}]_s$ nine-layered laminates were covered by Kevlar layers via vacuum assisted resin transfer molding.

Results

The numerical simulation results of velocity, impact energy, height and failure mechanisms of $[Ti/(0/90)_s/Ti]_s$ three-layered laminates were listed in Table 1. Also, the data of three-layered laminates due to 5 kg free drop tests were listed in Table 1 for contrast. The numerical results and the data 10 kg free drop tests were listed in Table 2 together. The numerical results and test data of $[Ti/(0/90)_2/\overline{Ti}]_s$ five layered laminates due to 5 kg free drop were tabulated in Table 3 and due to 10 kg free drop were listed in Table 4, respectively. The results and data of $[Ti/Kev/Ti(0/90)_2/\overline{Ti}]_s$ nine layered laminates due to 10 kg free drop were tabulated in Table 5.

The simulation picture of 5 kg free drop impact onto the five layered laminates at different height were shown in Fig.1. The pictures of damage impact for five layered laminates due to 5 kg free drop of height of 1.5m were shown in Fig. 2. The relationships of load and initial compliance vs. the height of free drop were plotted in Fig. 3.

Table 1. The numerical results and impact damage mechanisms of three layered samples due to 5kg free drop tests.

Velocity (m/s)	Energy (J)	Height of simulation (m)	Height of impact (m)	Damage model of simulation	Damage mechanisms of impact test
2.34	13.69	0.28	0.49	APC-2: f Ti:1st, f	Ti:1st, d; 2nd, f; depression: 5.79mm
2.43	14.76	0.30	0.53	APC-2: f Ti:1st and 2nd, f	-
2.47	15.25	0.31	0.55	APC-2: f Ti: 1st and 2nd, f	Ti:1st, d; 2nd, f; depression: 6.40mm
2.51	15.75	0.32	0.57	ballistic limit	-
2.62	17.16	0.35	0.62	p	Ti:1st, d; 2nd, f; depression: 6.71mm
2.80	19.6	0.40	0.71	p	Ti:1st, f; 2nd, f; depression: 7.02mm
2.97	22.05	0.45	0.79	p	Ti:1st, f; 2nd, f; depression: 7.72mm
3.13	24.49	0.50	0.88	p	Ti:1st, f; 2nd, f; depression: 8.04mm
3.28	26.90	0.55	0.97	p	Two samples near penetration, one penetrated; depression: 9.30mm
3.34	27.89	0.57	1.01	p	p

Notes: 1st denotes the first layer; 2nd denotes the second layer; d: depressed; f: fractured; p: penetration; APC-2: APC-2 laminates; Ti: Ti sheet; -: not available

Table 2. The numerical results and impact damage mechanisms of three layered samples due to 10kg free drop tests.

Velocity (m/s)	Energy (J)	Height of simulation (m)	Height of impact (m)	Damage model of simulation	Damage mechanisms of impact test
1.4	9.80	0.10	0.18	APC-2: f Ti: 1st and 2nd, f	Ti: d; depression: 5.01 mm
1.72	14.79	0.15	0.27	APC-2: f Ti: 1st and 2nd, f	Ti: Ti:1st, d; 2nd, f; depression:6.13 mm
1.77	15.66	0.16	0.28	ballistic limit	-
1.98	19.60	0.20	0.35	p	Ti: Ti:1st and 2nd, f; depression:7.41 mm
2.21	24.42	0.25	0.44	p	p
2.34	27.38	0.28	0.49	p	p

Notes: 1st denotes the first layer; 2nd denotes the second layer; d: depressed; f: fractured; p: penetration; APC-2: APC-2 laminates; Ti: Ti sheet; -: not available

Table 3. The numerical results and impact damage mechanisms of five layered samples due to 5kg free drop tests.

Velocity (m/s)	Energy (J)	Height of simulation (m)	Height of impact (m)	Damage model of simulation	Damage mechanisms of impact test
2.43	14.76	0.30	0.53	APC-2: f Ti: 1st, f	Ti: d; depression: 5.11 mm
2.62	17.16	0.35	0.62	APC-2: f Ti: 1st, f	-
2.80	19.60	0.40	0.71	APC-2: f Ti: 1st, f	Ti: 3rd, f; depression: 5.78 mm
2.97	22.05	0.45	0.79	APC-2: f Ti: 1st and 2nd f	-
3.13	24.49	0.50	0.88	APC-2: f Ti: 1st, 2nd and 3rd, f	Ti: 3rd, f; depression: 6.22 mm
3.19	25.44	0.52	0.92	ballistic limit	Ti: 3rd, f; depression: 6.52 mm
3.43	29.41	0.6	1.06	p	Ti: 3rd, f; depression: 6.96 mm
3.57	31.86	0.65	1.15	p	Ti: 1st and 3rd, f; depression: 7.20 mm
3.71	34.41	0.70	1.24	p	Ti: 1st and 3rd, f; depression: 7.63 mm
3.84	36.86	0.75	1.33	p	Ti: 1st and 3rd, f; depression: 7.85 mm
3.96	39.20	0.80	1.41	p	Ti: 1st and 3rd, f; depression: 8.00 mm
4.08	41.62	0.85	1.50	p	Ti: 1st and 3rd, f; depression: 9.10 mm

Notes: 1st denotes the first layer; 2nd denotes the second layer; 3rd denotes the third layer; d: depressed; f: fractured; p: penetration; APC-2: APC-2 laminates; Ti: Ti sheet; -: not available

Table 4. The numerical results and impact damage mechanisms of five layered samples due to 10kg free drop tests.

Velocity (m/s)	Energy (J)	Height of simulation (m)	Height of impact (m)	Damage model of simulation	Damage mechanisms of impact test
1.40	9.80	0.10	0.18	APC-2: f Ti: 1st, f	Ti: d; depression: 4.72 mm
1.98	19.60	0.20	0.35	APC-2: f Ti: 1st and 2nd, f	Ti: 1st, d; 3rd, f; depression: 6.09 mm
2.21	24.42	0.25	0.44	APC-2: f Ti: 1st, f,	-
2.30	26.45	0.27	0.48	ballistic limit	-
2.34	27.38	0.28	0.49	p	-
2.43	29.52	0.30	0.53	p	Ti: 1st, d; 3rd, f; depression: 7.44 mm
2.80	39.20	0.40	0.71	p	Ti: 1st, d; 2nd and 3rd, f; depression: 8.70 mm
3.13	48.98	0.50	0.88	p	Ti: 1st, 2nd and 3rd, f; depression: 9.56 mm
3.28	53.79	0.55	0.97	p	Near penetration; depression: 10.68 mm
3.43	58.82	0.60	1.06	p	p

Notes: 1st denotes the first layer; 2nd denotes the second layer; 3rd denotes the third layer; d: depressed; f: fractured; p: penetration; APC-2: APC-2 laminates; Ti: Ti sheet; -: not available

Table 5. The numerical results and impact damage mechanisms of nine layered samples due to 10kg free drop tests.

Velocity (m/s)	Energy (J)	Height of simulation (m)	Height of impact (m)	Damage model of simulation	Damage mechanisms of impact test
2.43	29.52	0.30	0.53	APC-2: f; Kevlar: f; Ti: 1st, f	-
2.62	34.32	0.35	0.62	APC-2: f; Kevlar: f; Ti: 1st 5th, f	-
2.80	39.2	0.40	0.71	APC-2: f; Kevlar: f; Ti 1st, 2nd and 5th, f	Ti, APC-2, and Kevlar, d; depression: 8.13 mm
2.87	41.18	0.42	0.74	APC-2: f; Kevlar: f; Ti: 1st, 2nd and 5th, f	-
2.97	44.1	0.45	0.79	APC-2: f; Kevlar: f; Ti: 1st, 2nd, 4th and 5th, f	-
3.13	48.98	0.50	0.88	APC-2: f; Kevlar: f; Ti: f	Ti: 1st-4th, APC-2, and Kevlar, d; Ti: 5th, f; depression: 8.13 mm
3.22	51.84	0.53	0.93	ballistic limit	-
3.28	53.79	0.55	0.97	p	-
3.43	58.82	0.60	1.06	p	Ti: 2nd-4th, APC-2, and Kevlar, d; Ti: 1st and 5th, f; depression: 9.68 mm
3.71	68.82	0.70	1.24	p	Ti: 2nd-4th, APC-2, and Kevlar, d; Ti: 1st and 5th, f; depression: 10.61 mm
4.08	82.23	0.85	1.50	p	Ti: 2nd-4th, APC-2, and Kevlar, d; Ti: 1st and 5th, f; depression: 11.61 mm

Notes: 1st denotes the first layer; 2nd denotes the second layer; 4th denotes the fourth layer; 5th denotes the fifth layer; d: depressed; f: fractured; p: penetration; APC-2: APC-2 laminates; Ti: Ti sheet; -: not available

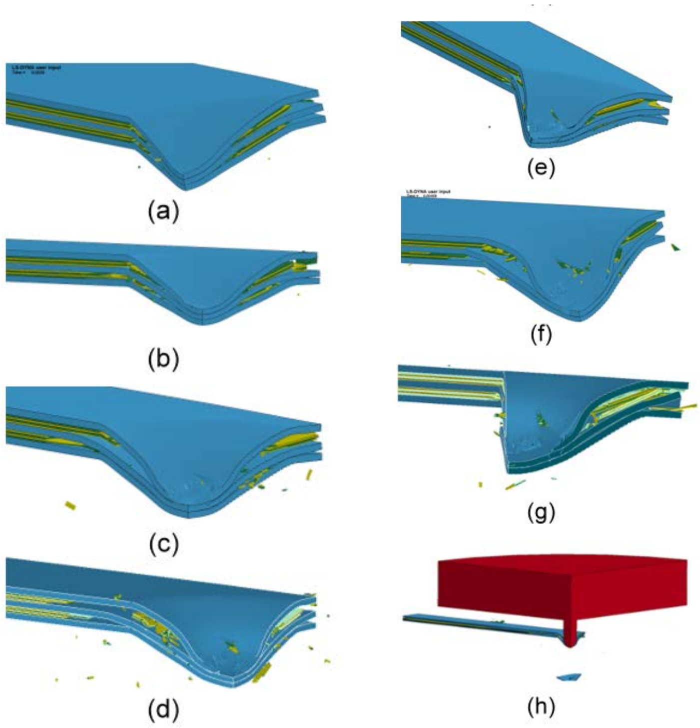

Fig. 1. Damage simulation pictures of five layered laminates due to 5kg free drop impact at heights (a) 0.2m (b) 0.25m (c) 0.3m (d) 0.35m (e) 0.4m (f) 0.45m (g) 0.5m (h) scheme of

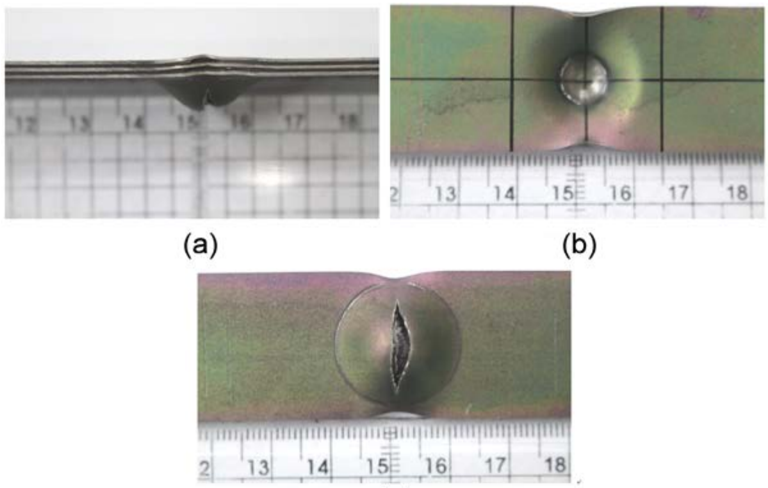

Fig. 2. The photos of impact damage on five layered laminates due to 5kg free drop at 1.5m high (a) side view (b) top view (c) bottom view.

Discussion

The numerical simulation by LS DYNA-3D software and finite element method we adopted first was to obtain the results as valuable information and references for the next step impact tests. Otherwise, the waste of many samples can not be avoided. Inversely, the test data provided an important contrast in comparison with the numerical results. We also found that the used software was acceptably feasible without the impact tests because the results were more serious damage than that of test data.

Due to the limited space of our lab the free drop impact tests were adopted alternatively. As can be seen in Tables 1-5 the real heights of free drop were much higher than those of predicted heights by simulation. It was mainly attributed to the friction of the testing system. To keep the same impact energy acting on the samples the heights adjusted and elevated were necessarily needed.

All the three types of samples after free drop impact tests were subjected to tensile tests as illustrated in Fig. 3. The general trend was that the applied loads decreased with the increasing height, however, the initial compliances of damage samples increased with the increasing height inversely.

Conclusion

Three types of Ti/APC-2 hybrid composite laminates were fabricated. The numerical simulation by using ANSYS LS DYNA-3D software and finite element method were completed to provide references for free drop impact tests. The equipments of free drop tests were set up. After all the impact tests the damage samples were due to tensile tests to obtain their residual capabilities of loads and compliances. The work can be concluded that the numerical results were more serious damage than those of test data. Thus, the adopted software was well acceptable. In the consideration of friction the height of free drop should be elevated to meet the requirement of equal impact energy in both testing and simulation.

References

[1] Asundi, A., & Choi, A. Y. N. (1997). Fiber metal laminates: An advanced material for future aircraft. *Journal of Materials Processing Technology, 63*(1-3), 384-394.

[2] Castrodeza, E. M., Ipina, J. E. P., & Bastian, F. L. (2002). Experimental techniques for fracture instability toughness determination of unidirectional fibre metal laminates. *Fatigue & Fracture of Engineering Materials & Structures, 25*(11), 999-1008.

[3] Dan-Jumbo, E., Leewood, A. R., & Sun, C. T. (1989). Impact Damage Characteristics of Bismaleimides and Thermoplastic Composite Laminates. 356-356-317.

[4] Ditchek, B. M., Breen, K. R., Sun, T. S., & Venables, J. D. (1980). *Morphology and composition of titanium adherends prepared for adhesive bonding.* Paper presented at the 25th National SAMPE Symposium.

[5] Dorey, G., Bishop, S. M., & Curtis, P. T. (1985). On the impact performance of carbon fibre laminates with epoxy and PEEK matrices. *Composites Science and Technology*, *23*(3), 221-237.

[6] Gunnink, J. W. (1988). Damage Tolerance and Supportability Aspects of Arall Laminate Aircraft Structures. *Composite Structures*, *10*(1), 83-104.

[7] Jen, M.-H. R., Tseng, Y. C., & Li, P. Y. (2007). Fatigue response of hybrid magnesium/carbon-fiber/PEEK nanocomposite laminates at elevated temperature. *Journal of the Japanese Society for Experimental Mechanics*, *7*(special issue), s56-s60.

[8] Jen, M.-H. R. C., C.-K.; Sung, Y.-C.; Hsu F.-C. (2010). *Fifth International Conference on Fatigue of Composites*. Paper presented at the Fifth International Conference on Fatigue of Composites, Nanjing.

[9] Jen, M. H. R., Chang, C. K., & Sung, Y. C. (2015). Fabrication and mechanical properties of Ti/APC-2 hybrid nanocomposite laminates at elevated temperatures. *Journal of Composite Materials*, *50*(15), 2035-2045.

[10] Joshi, S. P., & Sun, C. T. (1985). Impact Induced Fracture in a Laminated Composite. *Journal of Composite Materials*, *19*(1), 51-66.

[11] Khalili, S. M. R., Mittal, R. K., & Kalibar, S. G. (2005). A study of the mechanical properties of steel/aluminium/GRP laminates. *Materials Science and Engineering a-Structural Materials Properties Microstructure and Processing, 412*(1-2), 137-140.

[12] Lin, C. T., Kao, P. W., & Yang, F. S. (1991). Fatigue Behavior of Carbon Fiber-Reinforced Aluminum Laminates. *Composites, 22*(2), 135-141.

[13] Ramani, K., Weidner, W. J., & Kumar, G. (1998). Silicon sputtering as a surface treatment to titanium alloy for bonding with PEKEKK. *International Journal of Adhesion and Adhesives, 18*(6), 401-412.

[14] Sun, C. T., & Rechak, S. (1988). Effect of Adhesive Layers on Impact Damage in Composite Laminates. 97-97-27.

[15] Vlot, A. (1993). Impact Properties of Fiber Metal Laminates. *Composites Engineering, 3*(10), 911-927.

[16] Vlot, A. (1996). Impact loading on Fibre Metal Laminates. *International Journal of Impact Engineering, 18*(3), 291-307.

[17] Vlot, A., & Gunnink, J. W. (2001). *Fibre metal laminates : an introduction.*: Springer.

[18] Wu, C. L., Zhang, M. Q., Rong, M. Z., & Friedrich, K. (2005). Silica nanoparticles filled polypropylene: effects of particle surface treatment, matrix ductility and particle species on mechanical performance of the composites. *Composites Science and Technology, 65*(3-4), 635-645.

[19] Zhou, Y. X., Wang, Y., & Mallick, P. K. (2004). An experimental study on the tensile behavior of Kevlar fiber reinforced aluminum laminates at high strain rates. *Materials Science and Engineering a-Structural Materials Properties Microstructure and Processing, 381*(1-2), 355-362.