Residual Tensile Strength Analysis of Titanium-Carbon Fiber / PEEK Hybrid Laminates after Impact

Sapkota Bhuwan[a], Pan Lei[a]*, Ali Aamir[a],Zheng Zengmin[a],Tao Jie[a]

[a]College of Material Science & Technology

Nanjing University of Aeronautics and Astronautics, Nanjing 210016, China

*Email: bettypan@nuaa.edu.cn

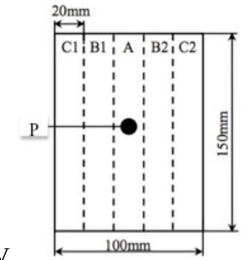
Abstract: The purpose of this study was to investigate the residual tensile behavior of titanium carbon fiber /poly-ether-ether-ketone (TA2-Cf/PEEK) laminates after impact. Laminates after impact were divided into 3 regions A, B, and C. The tensile strength of the subject after impact degenerates less than 30%, which indicates subjected Laminates have an excellent tensile strength. Two types of tensile fractures concluded in this paper are;instantaneous and relaxation type. The analysis result shows that the impact crack tip produces stress concentration, which grows along the transverse direction under the continuous external load, which leads to the final fracture of the sample.

Keywords: Configuration, fiber metal laminates, impact, residual tensile.

I.Introduction and Experimental Procedure

II.Fiber mental laminates (FMLs) are new kinds of composite material consisting of metal and fiber reinforced resin, which possesses the excellent properties of both metal and fiber. It has been widely applied in the aeronautics and astronautics fields due to its special properties such as outstanding fatigue resistance, impact resistance, corrosion resistance as well as fire resistance. This paper is aimed on the tensile strength after impact (TAI) of TA2-Cf/PEEK, a new derivative product of TiGr.

III.Six kinds of TA2-Cf/PEEK Laminates with 0°, 90°, orthogonal layers in 2 / 1, 3 / 2 structures were fabricated through the hot-press technology under the selected parameters. The impact experiment plan and the residual tensile strength experiment plan were formulated according to ASTM D7136-12 and ASTM D3039-07 respectively. The impact properties were comprehensively evaluated by the measurements of impact indentations, residual displacement and the length of cracks at the back surface of the impacted laminates, the ultrasonic C-scan method, and the residual tensile strength experiments. This paper is focused on investigating tensile fracture after the impact and residual tensile strength of TA2-Cf/PEEK Laminates after low-velocity impact. The nature of failure during the tensile test of six kinds of TA2-Cf/PEEK Laminates with 0°, 90°, orthogonal layers in 2 / 1, 3 / 2 structures impacted at low-velocity.For the quantitative analysis of TA2-Cf/PEEK laminate's strength further after low-velocity impact test, the impact-degraded samples of TA2-Cf/PE[1]EK were subject to tensile test. In this paper, according to ASTM D3039-07 [1] the residual tensile strength test of impacted TA2-Cf/PEEK samples were formulated.The tensile tests were carried out using the CMT-5105 universal tensile testing machine. The laminates after impact were divided into three regions (A, B, C) and impacted laminate was cut into tensile specimens (5 specimens), the length and width of 20 mm * 150 mm, the thickness determined according to sandwich structure. The tensile sample extraction from the impacted laminate is shown in Fig. 1.



IV.

V.Fig. 1. Sample extraction from impacted laminate (a) P is impact point (b) ---- cutting direction

VI.At the same time, to protect the gripping area and prevent the grip stress concentration and skid, reinforcement sheets were attached.

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- Corresponding author Pan Lei is currently assistant professor Nanjing University of Aeronautics and Astronautics, college of material science and technology, China, E-mail: bettypan@nuaa.edu.cn
- First Author Bhuwan Sapkota is currently pursuing masters degree program in Material Science and Engineering, E-mail: bhuwansata@icloud.com

*VII.*Result and discussion

A. *Ultrasonic C-scan after impact*

VIII.Fig. 2 and Fig.3 show the ultrasonic c-scan images of TA2-Cf/PEEK 2 / 1 and 3 / 2 structure laminates respectively after being impacted with various impact energies. The ultrasonic intensity information received by the ultrasonic probe reflects gray area, more the ultrasonic probe receives the ultrasonic intensity refracted from the laminate greater the gray area in the image. The gray area can be used to characterize better bonding of laminates. Meanwhile the dark region in the image represents delamination in the laminate from where ultrasonic probe did not receive ultrasonic intensity. In some images bonding area appears the phenomenon of uneven gray, which is because of uneven distribution of PEEK resin in the laminate. [4]

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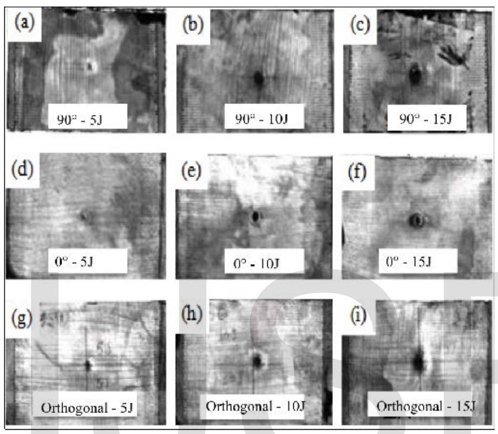
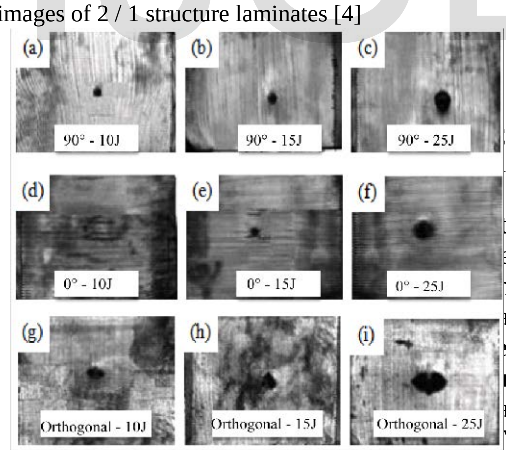


X.

XI.Fig. 2. Ultrasonic C-scan images of 2 / 1 structure laminates [4]



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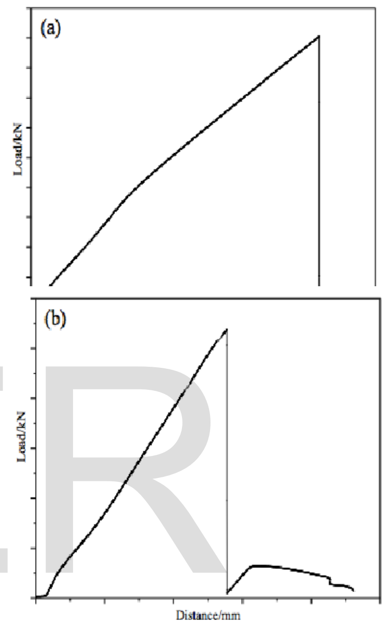
XIII.Fig. 3. Ultrasonic C-scan images of 3 / 2 structure laminates [4]

XIV.

*XV.*Through observation of C-scan image impact damaged sites can be found, damage area is only focused on the impact point within a certain range, no discrete expansion of the trend of damage, its shape basic oval, in addition, the long axis of the elliptical damage zone usually vertical in the laminate fiber laying direction.

B. *TA2-Cf/PEEK residual tensile strength analysis after impact*

XVI.TA2-Cf/PEEK Laminate as a metal and fiber reinforced composite material has the tensile characteristics of static mechanics of metal TA2 and carbon fiber at room temperature. From Fig. 1 sample extraction for tensile test after impact, impact damage zone theory should focus almost entirely on 'A' samples. Based on this, this paper will further validate the residual tensile strength experiment, and discuss the strength degradation situation of TA2-Cf/PEEK metal hybrid laminates under impact. Based on the analysis of tensile curves for 2 / 1 structures of TA2-Cf/PEEK the statistics show there are two types of tensile fractures; instantaneous and relaxation type. Fig. 4 shows two typical tensile curves for TA2-Cf/PEEK Laminates after impact.



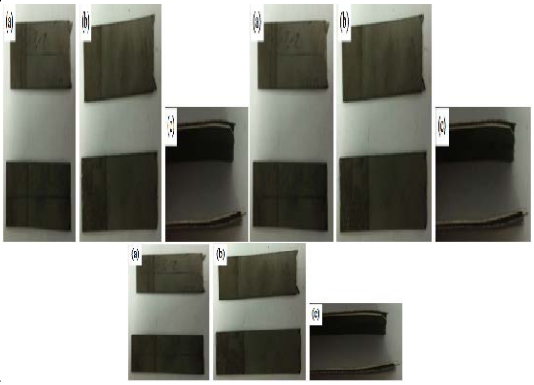
XVII.

4. Two kinds of F-d curves for tensile fracture in TA2-
f/PEEK Laminates after impact (a) Instantaneous (b)
elaxation

shown above, whether instantaneous or relaxation, tretching in early force – displacement (F-d) curve atisfies the linear relationship between TA2-Cf/PEEK in he initial tensile deformation and elastic deformation in aminates.

similarity in the early nature of the curves is due to nhancement of elastic modulus of TA2-Cf/PEEK aminates depends strongly on the fiber laying direction. The experimentally measured modulus of elasticity for 0-degree configuration of TA2-Cf/PEEK laminates was the highest, which was about 338gpa; followed by Orthogonal laying-up TA2-Cf/PEEK laminates which were about 141.3GPa; 90-degree laying-up TA2-Cf/PEEK Laminates with the lowest modulus of elasticity being only about 75.4GPa. Thus, along the direction of the carbon fiber in laminate, stiffness was significantly better than that of the other two categories laminates.

XXI.For instantaneous fracture, when the load exceeds the elastic limit of the carbon fiber, and the external load continues to increase, the noticeable sound of fiber fracture can be heard. Some of the images of the tensile fracture of the samples during the tensile test after impact are shown in Fig. 5.



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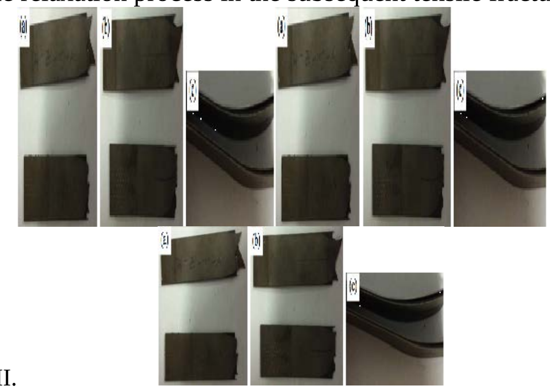
XXIII.Fig. 5. Instantaneous facture in 2 / 1 structures of TA2-Cf/PEEK tensile test after impact (a) Front side; (b) Rare side; (c) Lateral

XXIV.Can be observed from the Fig., metal TA2 layer in laminates have no noticeable plastic deformation, but a similar phenomenon of fracture at the edge of TA2 layers can be seen clearly from the Fig., TA2 plate fracture at the edge was 45 degrees, which is a typical type of macroscopic fracture toughness characteristics. Laminates with 90-degree of fiber configuration form a flat shape after fracture, whereas 0-degree configuration laminates forms rough layer upon fractures, these are typical brittle fracture macroscopic characteristics. At the same time, the instantaneous fracture is rarely observed due to the large area stretching stratification phenomenon. In summary, for instantaneous platelet from reaching the elastic limit to the whole process of fracture is very short, no plate process plastic deformation have fracture precursor, so the whole is the brittle fracture. In general, the tensile curve of 2 / 1 structures in the low-velocity impact and non-impact damage sample is instantaneous.

XXV.

XXVI.Unlike instantaneous plate fracture, relaxation plate fracture is reached in the elastic limit, and overall fracture does not occur immediately, the fracture process more embodies the plastic deformation behavior of titanium layer, but due to 2 / 1 structure, TA2-Cf/PEEK laminate strength at first tensile failure is produced as vast decline. Therefore, relaxation fracture of 2 / 1 structure TA2-Cf/PEEK Laminates still belongs to brittle fracture. Relaxation fracture of plates after macromorphology is shown in Fig. 6. Carbon Fiber Reinforced PEEK composites fracture morphology characteristic is consistent with the instantaneous fracture, but titanium plate in the tensile process features more obvious plastic deformation, titanium plate almost all fail along the length of sample all along the 45-degree direction. At the same time, the titanium plate in the middle appeared visible shrinkage neck phenomenon; as can be seen from Fig. 6 (c), the inner layers of tension will appear large area of delamination phenomenon. In general, laminates impacted with 10J and 15J of 2 / 1 structures in this paper is part of the relaxation process in the subsequent tensile fracture.



XXVII.

XXVIII.Fig. 6. 2 / 1 structure's relaxation type specimen fracture characteristics: (a) front; (b) back; (c) side

XXIX.

XXX.In this paper, the fracture of the TA2-Cf/PEEK laminates in the tension is based on either instantaneous mode or the relaxation type, which depends on the interface strength of the internal metal and the composite material. In this paper, the instantaneous fracture is controlled by laminate preparation process, in general, if the preparation quality is high, titanium and carbon fiber enhanced peek interface combined with the higher intensity. Laminates under tension are more likely to instantaneous fracture; influenced by the impact parameter, generally speaking, the impact energy is high resulting interlayer easier delamination, laminates under tension undergoes a the relaxation type fracture.

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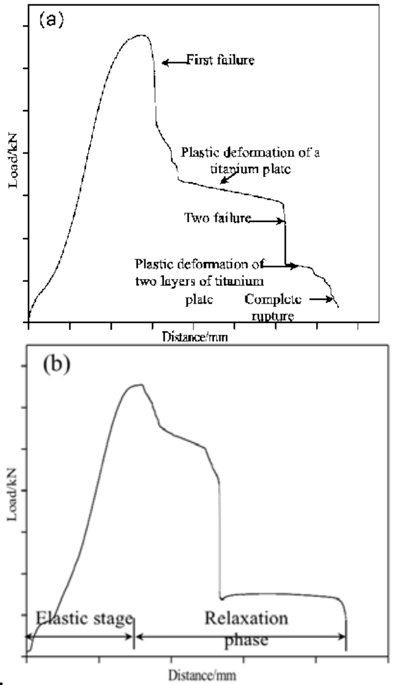
XXXII.TA2-Cf/PEEK 3 / 2 structure, have the same relaxation type and instantaneous type two kinds of fracture form. But due to more interface binding site tensile process of the interface will bear more load, the interlaminar stress easier to dispose of interface layer cracking threshold. Laminates in the tensile process more prone to stratification and 3 / 2 structures fracture tend to relaxation type fracture; Fig. 5 shows a typical tensile curve for 3 / 2 structure TA2-Cf/PEEK laminates. Similar to the 2 / 1 structural relaxation type laminate tensile fracture process, the tensile fracture process of 3 / 2 structure is divided into elastic phase and the relaxation phase. But different from the 2 / 1 structure relaxation type curve, the plastic deformation characteristics of 3 / 2 structure plate in tension relaxation period is more apparent, which is mainly embodied in the two "inclined platform".

XXXIII.



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XXXV.Fig.7. Typical 3 / 2 structure of TA2-Cf/PEEK Laminates after impact tensile F-d curve: (a) no impact damage; (b) with impact damage

XXXVI.As shown in Fig. 7 (a), for the TA2-Cf/PEEK laminates without impact damage, when the applied tensile load exceeds the elastic limit, the laminate has the first failure and the strength is reduced by about 40%. Followed by the first layer of the titanium plate to bear the load, the curve appeared in the "ramp platform," the internal stress of the plate showed a slow downward trend, which is due to the plastic deformation caused by the titanium plate. When the first layer of titanium plate after complete rupture, Fig. curve appears again "cliff". At this time, happen in the laminated plates secondary failure, the load is mainly undertaken by the last layer without fracture of the titanium plate, curve appeared the second inclined platform ". Because the last layer of the titanium plate in the pre-stretching process has produced significant plastic deformation, sharp internal dislocation proliferation, the last layer of titanium plate dislocation slip under the effect of rapid fracture, section two "inclined platform" process is relatively shorter. For TA2-Cf/PEEK Laminates containing impact damage, due to the damage caused by the impact, the first layer of impact damage site of titanium laminate's crack under tensile loading has been expanding rapidly. Resulting in failure, so the first "oblique platform" is short, as shown in Fig. 7 (b).

XXXVII.The morphology of the tensile test specimen of 3 / 2 structure TA2-Cf/PEEK laminates is presented in Fig. 8. A significant amount of plastic deformation was produced in the tensile fracture site, and the fracture was 45 degrees. At the same time, there was a vast area between the Cf/PEEK and the titanium plate.

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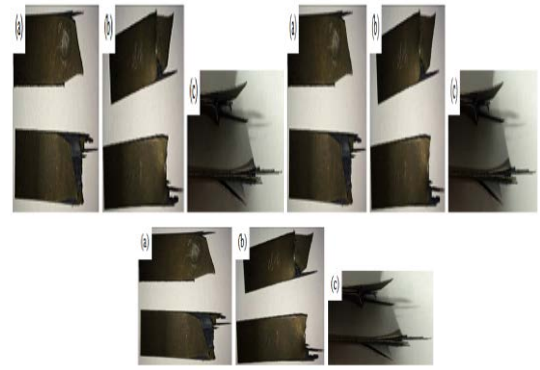

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rupture with fiber breakage and titanium plate plastic deformation, first failure strength decreased only about 40%.

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C. *Tensile strength of TA2-Cf/PEEK Laminates after impact*

XLII.The strength of each area of the TA2-Cf/PEEK laminate for 2 / 1 structure and 3 / 2 structure after impact is shown in table 1 and table 2.

XLIII. Table 1 tensile strength of 2 / 1 TA2-Cf/PEEK laminates after impact (strength unit: MPa)

.St.	.Layer	I.Area	I.Impact energy			
			I.0 J	.5 J	.10 J	I.15 J
I.2/1	I.0°	.A	.732.06	I.726.50	I.647.43	I.653.53
		.B	.742.93	I.733.61	I.740.21	I.835.02
		.C	.691.59	I.680.05	I.665.99	I.663.75
	.Degradation percentage of tensile strength after impact		./	I.-2.78%	I.7.92%	I.15.99%
	.90°	.A	I.445.23	I.465.58	I.357.43	.349.50
		.B	I.451.37	I.452.31	I.400.10	.443.73
		.C	I.437.52	I.471.18	I.421.10	.439.20
	.Degradation percentage		I./	I.-1.54%	I.12.95%	.20.97%
	.Orthogonal	I.A	I.652.74	I.677.13	.607.01	.496.40

		I.B	I.637.89	I.665.46	V.725.52	V.680.72
		I.C	I.606.96	I.688.79	X.638.45	X.621.46
	I.Degradation percentage		I./	I.-0.58%	V.10.99%	V.18.21%

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CXX. Table 2 tensile strength of 3 / 2 TA2-Cf/PEEK laminates after impact (strength unit: MPa)

I.St.	**I.Layer**	**I.Area**	**V.Impact energy**			
			V.0 J	I.10 J	I.15 J	I.25 J
X.3/2	X.0°	I.A	I.715.41	I.738.60	V.796.91	V.665.09
		I.B	I.732.97	I.643.73	X.777.90	L.752.52
		I.C	I.698.80	I.665.75	V.747.00	V.797.61
	I.Degradation percentage of tensile strength after impact		I./	I.-13.44%	X.-4.52%	L.16.61%
	I.90°	I.A	I.309.88	V.285.64	V.279.34	I.242.11
		I.B	I.341.52	X.288.40	X.307.90	I.318.41
		I.C	I.332.33	V.272.66	V.315.27	I.352.44
	I.Degradation percentage		I./	X.-0.88%	X.9.99%	I.27.82%
	I.Orthogonal	I.A	V.614.52	V.615.65	I.564.57	I.574.43
		I.B	X.648.03	X.577.85	I.528.13	I.636.79
		I.C	V.657.46	V.632.00	I.638.27	I.679.75
	I.Degradation percentage		X./	C.-3.31%	I.3.19%	I.11.78%

CXCIII.

CXCIV.Analysis of tensile strength of each region of TA2-Cf/PEEK laminates without impact (0 J) for 2 / 1 Structure of 0-degree configuration, 90-degree, and orthogonal configuration are averaged 722.19MPa, 448.04MPa and 632.53MPa respectively. The tensile strength of non-impacted samples for 3 / 2 and 2 / 1 Structures of the same configuration had no significant difference. The high tensile strength of the fiber metal laminates along the laying direction shows the high strength of carbon fiber in this case. At the same time, through the comparison of the tensile strength of different regions A, B and C the value are slightly affected by the weight drop impact experiment on laminates. Tensile strength can be found such that the tensile strength of region A was significantly lower while the B and C regions, intensity values remained almost intact on the strength level of the un-impacted laminate. This phenomenon can be explained by the impact damage concentrated in area A did not extend to region B and C. Impact damage of TA2-Cf/PEEK laminate is limited only to the smaller range (A), providing excellent resistance to impact damage propagation. This is consistent with the results obtained from ultrasonic C-scan in the previous section A.

CXCV.strength of A specimens with impact damage is higher than that of B and C samples. Previous ultrasonic C-scan image evaluation results showed that 2 / 1 structure laminates at 5J impact energy have a slightly small area layer cracking, but this did not cause the laminate's strength degradation.When the impact energy is increased to 10J and 15J, laminate's impact damage site was increased, and resulting the strength to decrease, the degree of degradation of laminates was affected by fiber laying-up direction. For 2 / 1 structure unidirectional 0-degree TA2-Cf/PEEK Laminates after 15J impact strength remains above 650 Mpa, the tensile strength value is higher than the vast majority of high-quality carbon steel.

*CXCVI.*Similarly, for the 3 / 2 structure of the laminates, the degradation of the laminate was also affected by the fiber layup direction, the impact strength of the laminates from high to low in order; 0-degree, orthogonal laminates, and unidirectional 90-degree.

D. *Analysis of tensile fracture mechanism of TA2-Cf/PEEK metal hybrid laminates after impact*

CXCVII.The TA2-Cf/PEEK Laminates after impact has two kinds of fracture modes, instantaneous, and relaxation type. When impact energy is below the critical value, the damage in the laminates is not sufficient to cause layer cracking and strength degradation, resulting in the tendency to instantaneous fracture. When the impact energy is high enough, inner layer already contains delamination damage resulting the plate tendency to relaxation type fracture. That is, the impact energy would lead to a greater degree of damage in the laminates. Therefore, the vast majority of impact damage containing laminates follow relaxation fracture mode, this paper mainly discussed ways of relaxation type fracture process and fracture mechanism.

CXCVIII. The tensile fracture process of the 3 / 2 structure of unidirectional 0-degree laminate at 25 J impact is presented in this paper as shown in the following Fig.

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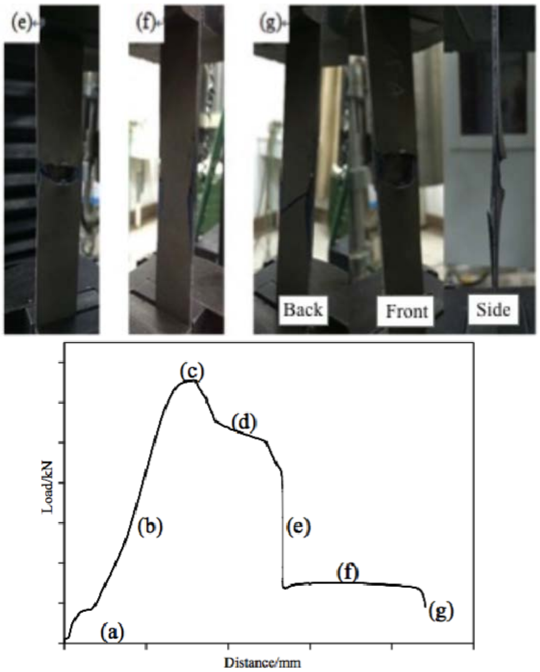

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CCII.Fig. 9. 3 / 2 structure tensile fracture process of unidirectional laminates 0-degree 25 J impact

CCIII.

CCIV.At the initial stage of the tensile loading, the TA2-Cf/PEEK 0-degree laminate sample under tensile fracture of carbon fiber in early still not unable to bear most of the load. But due to the impact load, stratification occurs laminates around impact craters, and impact craters on the back of metal plate seem to bore further damage vertical to the fiber direction. So when the tensile load applied along the axis of the sample, hierarchical and non-hierarchical interface part and the back surface of sample both ends of crack will still produce a greater degree of stress concentrated, and the laminate fails by instantaneous fracture. With the external tensile forces continue to increase, the fiber axial stress reached the maximum tensile strength value and produces coalescence fracture, namely the first failure. At this point, the external load is mainly borne by the titanium plate, the resin matrix produces elastic deformation under the external force, and the titanium plate has apparent plastic deformation, the tensile curve showed a downward sloping platform at point (c). At the same time, due to the increased external loading, the crack formed at the point of the impact will gradually grow along the transverse direction to the entire titanium plate width, so that the titanium plate fractures, resin matrix also immediately breaks, that is, the second failure. The two failures reduce the strength of the laminate significantly, and the external load is concentrated on the layers of the titanium plate, which is similar to the "yield" plastic deformation process, thus complete rupture of laminates.

CCV.The fracture process of the laminates with 90 degree and orthogonal layup has a similar mechanism; both are based on crack initiation, propagation, and eventually leading to the failure of the laminate. But the difference is 90-degree laminates, and orthogonal laminates crack direction is parallel to the tensile direction. Although the type II fracture can also cause severe stress concentration phenomenon, most of the time cracks will not be directly extended, when the stress level reaches titanium plate type I fracture initiation threshold value of KIC (stress intensity). At the tip or impact craters, positive initiation mode I crack will initiate and propagate outward resulting in the fracture.

III.Summary

CCVI.According to the qualitative and quantitative experimental evaluation of the different structure, different laying layer TA2-Cf/PEEK Laminate's residual tensile strength test after impact damage performance, some important conclusions were obtained as following:

CCVII.1) TA2-Cf/PEEK Laminates are affected by the initial impact energy. For the same kind of TA2-Cf/PEEK Laminates, with the increase of the impact energy, plastic deformation, crack and other macro impact damage behind the crack become more obvious, the laminate's internal delamination phenomenon is more serious, resulting in the greater degradation of tensile strength.

CCVIII.2) The impact properties of TA2-Cf/PEEK Laminates under the influence of layup sequence. Orthogonal laminates with higher stiffness properties, excellent resistance to plastic deformation caused by impact load, but orthogonal laminate resistance behind cracking and resistance combined with the poor performance of interface delamination. At the same time, from the analysis of the residual tensile strength, orthogonal laminate's original tensile strength and resistance to impact strength degradation is inferior to unidirectional 0-degree laminates. Based on the analysis of various aspects, this paper considers that the unidirectional 0-degree TA2-Cf/PEEK Laminate has excellent impact resistance.

CCIX.3) Carbon fiber as the reinforcement, the variation of layup sequence in TA2-Cf/PEEK Laminates will produce anisotropy, a series of features in the unidirectional enhancement during impact process of the laminates is closely related to fiber layup sequence. In general, the laminates along the carbon fiber direction have a high impact resistance cracking, delamination growth performance, and higher residual tensile strength even after impact.

CCX.4) The characteristics of the tensile process of TA2-Cf/PEEK Laminates after impact were analyzed, and the two types of fracture modes are summarized. Transient fracture is a more brittle fracture, and the relaxation type fracture contains more plastic deformation characteristics, there are many evolution stages before the complete fracture of the laminate. The way in which the plate fractures depend on the bonding effect and damage due to the impact on the laminate. In general, 2 / 1 structure regions not affected by the impact of laminates and is bonded well, so it has good performance in transient mode fracture; 2 / 1 structure containing impact damage zone

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laminates and 3 / 2 structure to the vast majority have relaxation type fracture.

CCXI.5) The impact will cause the degradation of tensile strength regardless of the layup of TA2-Cf/PEEK Laminates. For 2 / 1 structure TA2-Cf/PEEK Laminates, when the impact energy in 5J below, the impact is not enough to cause the degradation of the strength of the laminates; when the impact energy is 15J, the strength deterioration of the laminate is only about 20%. For 3 / 2 structure TA2-Cf/PEEK Laminates the impact caused strength degradation for energy critical value higher than at least 10J, unidirectional laminates of 0-degree the critical value should be more than 15J. At maximum 25J impact laminate's strength degradation is below 30%, unidirectional 0-degree and orthogonal laminate’s tensile strength after impact is still higher than the vast majority of high-quality carbon steel.

CCXII.

CCXIII. Acknowledgement

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CCXV.

CCXVI.

CCXVII.References

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