FULL LENGTH PAPER

BALLISTIC PERFORMANCE OF THERMALLY EXPOSED CFRP COMPOSITES

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Abstract

In this investigation, high velocity impact test was carried out to study the after effect of thermal loading on ballistic limits of composite laminates. Plain woven carbon/epoxy laminates with nominal thickness of 2.3 mm were fabricated by compression moulding technique. To study the effect of thermal loading, laminates were exposed to different temperatures of 60°C, 80°C, 100°C, 120°C, 140°C and 160°C for 24 h in hot air oven and brought back to room temperature. Impact test was carried out using single stage gas gun for velocity up to 115 m/s. The bullet used was ∅ 9.6 mm and mass 14.20 gm. The results show that ballistic limit reduces from 83 m/s to 62 m/s with increase in loading temperature from 30°C to 160°C. For impact velocity above ballistic limit, energy absorbed by the laminates reduces with increase in loading temperature. Shear plug formation was observed during experiment as reported in literatures [4, 5 and 6]. An energy base mathematical model is employed to predict the ballistic limit. The model considered the energy loss due to various failure mechanisms that occurred during impact test. The predicted ballistic velocity and energy absorbed by laminates show good agreement with the experimental results.

***Keywords**: Carbon/epoxy composite; High velocity impact; Ballistic limit; Thermal loading*

Nomenclature

a = Notch length
A_{delam} = Area of delamination
b = Width
C_e = Elastic wave velocity
C_p = Plastic wave velocity
C_t = Transverse wave velocity
D = Diameter of projectile
E = Young's modulus of CFRP
E_A = Energy absorbed by laminate
E_c = Area under stress-strain diagram of CFRP in tension test
E_E = Young's modulus of epoxy
E_o = Initial impact energy of projectile
E_r = Residual energy of projectile
E_{TF} = Energy absorbed due to primary fibres
E_{mc} = Matrix cracking energy
E_{MC} = Energy absorbed due to matrix cracking
E_{ED} = Energy absorbed by secondary fibers
E_{DL} = Energy absorbed due to delamination
E_{SP} = Energy absorbed during shear plug formation
E_{MV} = Energy absorbed due to moving cone
G_{23} = Shear modulus
G_{IIc} = Critical dynamic strain energy release rate in mode II
L = Half-length between supports
L_{gauge} = Gauge length of target
M_P = Mass of projectile
M_C = Mass of moving cone

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p	= Maximum load
R_c	= Radius of cone
RT	= Room temperature
S_{sp}	= Shear plug strength
h	= Thickness of laminate
V_i	= Impact velocity
V_r	= Residual velocity
V_f	= Fiber volume fraction
V_{50}, V_{50S}	= Ballistic limit
ρ	= Density of composites
Δt	= Impact duration
$\dot{\varepsilon}$	= Strain rate
ε_o	= Elastic strain
ε_p	= Plastic strain
δ	= Maximum deflection

Introduction

Recent trend shows that there is tremendous increase in the use of FRP materials in aerospace, civil, automobile and military applications which is due to superior properties like specific strength, specific stiffness, resistance to corrosion, low conductivity etc. The composites properties are dependent on various parameters like fiber volume fraction, fiber orientation, thickness, matrix properties, fabrication process and operating conditions. Composites are subjected to harsh environmental conditions like impact loading, thermal loading etc. in aerospace and military applications. Thus the behavior of composites needs to be understood in various operating conditions for effective use of composites. Composites used for structural components in automobiles, aerospace and military applications need to be survived against impact loading as they are prone to impact damage. Cantwell et al. [1, 2] studied low and high impact perforation behaviour of carbon reinforced composites and revealed that under high velocity impact, target geometry does not affect the perforation energy as high velocity impact is a localised phenomenon. Lopez et al. [3] carried out high velocity normal and oblique impact tests on thin woven carbon/epoxy laminates by steel bullet of 1.73 gm for velocities between 70 to 531 m/s. Results showed that damage area increased with increase in impact velocity and became maximum at ballistic limit. Thereafter, it reduced and became almost constant at higher velocities. Naik et al. [4] presented analytical formulation for energy absorption during high velocity impact on woven fabric composites. The formulation considered different damage and energy absorption mechanisms which include tension in primary fibers, deformation of 2nd fibers, delamination, matrix cracking, shear plug and friction during penetration. Hazell et al. [5] performed normal and oblique impact penetration on 3 mm and 6 mm woven carbon/epoxy laminates. It was reported that for 6 mm plate, perforation at lower velocities was dominated by tensile failure of rear weave. whereas, ejection of conical mass from laminates was observed for velocity higher than 170 m/s. For thin laminates delamination area was constant regardless of impact energy. Hazell et al. [6] studied the ballistic performance of two bonded CFRP laminates impacted by steel sphere. The energy absorbed/thickness of bonded laminates was more compared with non-bonded laminates. J. Perez Martin et al. [7] conducted impact behaviour of hybrid composites made up of woven carbon and glass/epoxy laminates. It was observed that hybrid composites possessed higher energy absorption capacity than carbon epoxy laminates. Position of glass fiber plies was more significant than the amount of hybridization. It was observed that closer the glass fiber layer from rear surface better was the performance of laminates. Rahul et.al. [8], conducted experimental and analytical study of high velocity impact on Kevlar/epoxy laminates, to study the effect of thickness and lay up sequence. The study showed that 0/90 layup was the most efficient for energy absorption. During service life, composites may be subjected to higher temperature than the operating conditions due to heat generated by other components in the system. Shigeki et al. [9] studied the effect of thermal loading and thermal shock on ballistic properties of Sic/Sic composite at 600°C and 1000°C. Results showed that there was degradation in ballistic properties by thermal loading, but no significant effect of thermal shock over gradual cooling. The projected damage area on front and back was independent of thermal loading and varied with impact velocity. Min-Hwan Song et al. [10] conducted bearing strength test on carbon/epoxy lap joint after thermal loading at different temperature and time durations in dry oven. It was observed that with increased in thermal loading by time and temperature, the bearing strength of carbon/epoxy lap joint was reduced. Most of the available literatures were carried out to understand the physics of damage mechanism, and to study the effect of stacking sequence, material characteristics, impact angle, and projectile characteristic during impact. But limited work was done to study the effect of environment conditions on ballistic performance of composites. Thus in this study an attempt is made to understand the after effect of thermal loading on ballistic property of carbon/epoxy laminates.

Material Used

Plain woven carbon fabric of 500 gsm, epoxy LY 556 resin and HY 991 hardener were used as raw material for composite manufacturing. Nominal thickness of 2.3 mm composite laminates were prepared by using compression molding technique at curing temperature of 80°C. Laminate consists of 5 layers of woven fabric in (0/90) orientation. The density achieved was ~1550 kg/m3 and fiber volume fraction achieved was ~0.68. Thermal loading of laminates at various temperatures was done by using hot air oven. Samples were placed in hot oven for 24 h at different temperature with an accuracy of $\pm$ 2°C followed by gradual cooling. The material properties of CFRP laminate were obtained by conducting basic mechanical test as per ASTM standards. Along with this, static punch test was also carried out to determine shear plug strength. Properties obtained for woven CFRP laminate with different thermal loading are summarised in Table-1. These are the average of three best values of five samples. The variation of values is less than 5%.

Experimental Methodology

Impact test was performed using a single stage gas gun for velocities up to 115 m/s, the setup is shown in Fig.1. The gas gun consists of a barrel (length of 2 m and diameter 10 mm), firing chamber, pressure regulators and compressor. The variation in velocity was obtained by changing the pressure of gas inside the firing chamber. Projectile used was hardened steel cylindrical bullet with length 15 mm and $\varnothing$ 9.6 mm. Test specimens of dimension 130 mm x 130 mm were gripped at four edges by using C-clamps on rigid target plate as shown in Fig.2. Impact and residual velocity of projectile were measurement with an error of < 2%by phantom high speed camera at frame rate of 18000 per second.

Energy absorbed by laminate is calculated by using energy balance equation

$$E_A = \frac{1}{2} m \left(V_i^2 - V_r^2 \right) \tag{1}$$

Where, m is mass of projectile, V_i and V_r are the impact and residual velocities respectively.

Experimental Results

Impact Velocity Below Ballistic Limit

When Impact velocity was below ballistic limit the damage in carbon/epoxy laminates was not visible through naked eyes. At velocity close to ballistic limit visible damage was seen (Fig.3) in all the samples, the damage patterns were circular in shape and almost equal to the diameter of bullet that signifies shear failure of front face. Whereas, marginal bulging appeared on back surface of samples, which show that fibers were in tension during impact, which was also reported in [3-8, 11, 12]. In the experimental investigation, it was seen that the energy absorbed by laminates increased up to ballistic limit irrespective of thermal loading.

Ballistic Limit

Ballistic limit is defined as the minimum impact velocity needed for full penetration of the target with zero exit velocity. There are various graphical and analytical methods to determine ballistic limit. Mean Limit Velocity V_{50S} approach is simple and straight forward method, according to this, V_{50S} is a mean of three highest striking velocities at which no perforation occurs and the three lowest velocities at which perforation occurs. Mean Limit velocity method was employed to determine the experimental ballistic velocity.

Table-1 : Material Characterisation of CFRP

S. No.	G_{IIc} kJ/m^3	Matrix Cracking Energy MJ/m^3	Shear Plug Strength MPa	Tensile Test			
				E_y GPa	Stress MPa	Strain mm/mm	E_c MJ
Room Temp	0.764	1.45	84.13	66.25	788	0.01	3.94
60°C	0.722	1.73	75.63	66.12	781	0.01	3.90
80°C	0.554	1.68	75.48	61.69	756	0.009	3.4
120°C	0.526	1.58	58.38	59	543	0.0088	2.38

Figure 4 shows the embedded bullet and formation of petalling on the back surface of sample. Similar observation was also reported by Hazell et al. [5]. The same effects on thermally exposed samples were seen irrespective of exposed temperature.

For Room Temperature (RT)samples the ballistic velocity obtained was 83.3 m/s. whereas, it was 74 m/s for 60°C exposed samples,, which is 12.3 % less than the RT sample. Similarly, 12.3 %, 22.4 % and 25.5 % reduction in ballistic limit were seen in 80°C, 100°C and 120°C thermally loaded samples, respectively (Fig.5). Similar trends were reported in Shigki et al. [9]. Curve fitting is done, which is a 2nd order polynomial equation with adj R-square of 0.958. The equation is

$$y = 95.466 - 0.4329x + 0.00127\, x^2 \qquad (2)$$

It is seen that ballistic limit is reduced with increase in thermal loading and has come down to 62 m/s for 160°C exposed samples, which is 25.5% less than the room temperature samples. It is also seen that ballistic limit is almost same for 120°C, 140°C and 160°C samples, which might be due to the thermal degradation of composite as the samples were exposed to temperature higher than T_g of epoxy resin which is in the range of 100 to 120°C.

Impact Velocity Above Ballistic Limit

At ballistic limit, there was an increase in energy absorption by the laminates as the contact time between target and projectile was more due to perforation. Therefore energy absorbed by all mechanisms was more.

Experiments for velocities above ballistic limit were carried out for RT, 60°C, 80°C, 100°C, 120°C and 140°C exposed samples. With increased in impact velocity above ballistic limit, the energy absorbed by laminates became constant for velocities up to 115 m/s. For room temperature samples average energy absorbed was 44 J. Whereas, the energy absorbed by 80°C, 100°C, 120°C and 140°C loading samples were 32J, 32J, 26J, 27J respectively as shown in Fig.6. Results showed reduction in energy absorption by carbon/epoxy laminate with increase in loading temperature. This trend might be due to thermal degradation of epoxy resin.

The sequence of projectile impact on laminates at velocity of 115 m/s is shown in the Figs.7 and 8. Formation of shear plug (Fig.7, 8 and 9) was seen for velocities above ballistic limit. Shear plug formation during impact of CFRP was also reported in [3-6, 14]. With increase in thermal loading, projectile perforation and plug formation occurred at lower impact velocity when compared to room temperature samples. Fig.10 shows the impact velocity vs. residual velocity. Above ballistic limit it is seen that for a particular impact velocity, residual velocity of projectile increases with thermal loading.

To understand the failure mechanisms of carbon/epoxy composite during high velocity impact, SEM (Scanning Electron Microscope) images were taken for shear plugs. Fig.11shows the shear plug of RT sample. It is seen that top surface fibers and matrix has clear fracture that signifies shear failure. Whereas, rear surface of shear plug, appeared to have fiber pull outs which shows tensile failure due to bending during cone formation, that is also seen in Fig.12. Similar observations were made by Hazell et al. [5, 6, and 14]. For thermal loading samples, similar findings were observed irrespective of exposed temperature. That signifies that failure mechanisms are independent of thermal loading.

Analytical Model

An energy based model is proposed to predict the ballistic limit of carbon/epoxy laminate. From literature and experimental observation it is seen that the energy absorbed by the different mechanisms consist of primary fiber failure, elastic deformation of secondary fibers, matrix cracking, delamination, shear plug and energy absorbed by cone formation. By using energy balance during impact event, the sum of energy absorbed by different mechanisms and the residual energy of projectile must be equal to impact energy of projectile.

Following assumption are made for model development:

- Projectile is considered as rigid and energy absorbed is negligible compared to total impact energy.
- Friction between the target and projectile is negligible.
- Material properties remain constant during impact.
- Failure mechanism of composite is uniform across the thickness.
- Fiber failure in one lamina does not affect the failure of other lamina.

The initial impact energy of projectile is given by

$$E_o = \frac{1}{2} M_p V_t^2 \tag{3}$$

Residual energy of projectile after penetration is given by

$$E_r = \frac{1}{2} M_p V_r^2 \tag{4}$$

During the impact, wave formation occurs in longitudinal and transverse direction. Longitudinal wave propagates in fiber plane outward along the filament. The longitudinal wave velocity is given by

$$C_e = \sqrt{\frac{E}{\rho}} \tag{5}$$

$$C_p = \sqrt{\frac{1}{\rho}\left(\frac{d\sigma}{d\varepsilon}\right)} \tag{6}$$

Whereas, the plastic wave velocity is given by Eq.(6). Since there is no plastic deformation in carbon/epoxy composite, the plastic wave travels with same velocity as that of elastic wave.

Transverse wave which causes cone formation at the back surface of target plate travels with a speed of

$$C_t = \sqrt{\frac{G_{23}}{\rho}} \tag{7}$$

The radius of cone formation depends on time duration of impact event. The time duration of event depends on strain rate which is given by [8]

$$\Delta t = \frac{\Delta \in}{\dot{\in}} \tag{8}$$

Whereas

$$\dot{\in} = \frac{V_o}{L_{gauge}} \tag{9}$$

Thus, radius of cone formed is given by [8]

$$R_c = C_p \Delta t \tag{10}$$

Energy Absorbed Due to Primary Fibers

During impact, primary fibers are under tensile loading due to cone formation at the back surface. This causes fiber failure at the impact zone and plastic deformation of primary fibers. The total energy absorbed by primary fibers is given by [8]

$$E_{TF} = \frac{\Pi}{4} D^2 h E_c + \left(4 R_c h D - \frac{\Pi}{4} D^2 h\right) E \in_p^2 \tag{11}$$

Elastic Deformation of Secondary Fibers

Fibers other than primary fibers are considered as secondary fibers and undergo elastic deformation due to cone formation. The energy absorbed by the secondary fibers is dependent on strain variation in fibers. Near the impact zone the stain is equal to maximumelastic strain whereas at the boundary it is almost zero. In the present study, strain variation is considered as linear. Therefore strain variation in fibers can be expressed as

Boundary condition, $\in = \in_o$ at r = d and $\in = 0$ ar $r = R_c$

$$\in = \frac{2 (R_c - r)}{(2 R_c - D)} \in_o \tag{12}$$

Energy absorbed/volume by the secondary fibers is given by

$$E_{ED} = \frac{1}{2} E \in^2 \tag{13}$$

Thus, total energy absorbed during secondary fiber deformation is [18]

$$E_{ED} = h \int_{D/2}^{R_c} \frac{1}{2} E\, 2\pi r\, 4 \in_o^2 \left(\frac{R_c - r}{2 R_c - D}\right) d r^2 \tag{14}$$

$$E_{ED} = \frac{\pi E \in_o^2 h}{(2 R_c - D)^2} \frac{R_c^4}{3} - \left[\frac{D^2 R_c^2}{2} + \frac{D^3 R_c}{3} - \frac{D^4}{16}\right] \tag{15}$$

Shear Plug Formation

Shear plug formation was seen during experiment, which is one of the significant energy absorption mechanisms. It was observed that thickness of shear plugs formed during experiment was consistently half of the laminate thickness, which indicates that at the point of impact, shear failure occurred in the front face, is limited to the half of laminate thickness. Where as, other half of the laminate fail due to tensile failure during impact. Thus energy absorbed by shear plug formation is given by

$$E_{SP} = \frac{\Pi D h^2 S_{sp}}{2} \quad (16)$$

Energy Absorbed Due to Delamination and Matrix Cracking

During impact, transverse wave is generated followed by plastic wave which causes matrix cracking and delamination between the layers. The energy absorbed by matrix cracking and delamination are given below:

Energy Absorbed due to delamination

$$E_{DL} = \Pi R_c^2 G_{IIcd} \quad (17)$$

Energy absorbed due to matrix cracking

$$E_{MC} = \Pi R_c^2 h E_{mc} (1 - V_f) \quad (18)$$

Energy Absorbed Due to Moving Cone

Transverse wave at the time of impact causes cone formation at the back surface of target plate. This forward motion of cone absorbs energy and causes retardation in the projectile velocity. This retardation of projectile is considered to be at constant deceleration.

Mass of the moving cone formed at the end of impact event is given by

$$M_c = \pi R_c^2 h \rho \quad (19)$$

Initially it is considered that velocity of moving cone is same as the impact velocity of projectile i.e. V_i and at the end of impact event the cone velocity is considered as residual velocity of projectile V_r.

Thus, the energy absorbed by cone formation is given by [8]

$$E_{MV} = \frac{1}{16} M_c [V_i + V_r]^2 \quad (20)$$

At ballistic limit, $V_r = 0$

$$E_{MV} = \frac{1}{16} M_c [V_i]^2 \quad (21)$$

Now by energy conservation

Total energy balance is given by

$$E_o = E_{TF} + E_{ED} + E_{SP} + E_{DL} + E_{MC} + E_{MV} + E_r \quad (22)$$

$$E_o = E_o' + E_{MV} + E_r \quad (23)$$

$$E_o = E_o' + \frac{1}{16} M_c [V_i + V_r]^2 + \frac{1}{2} M_p V_r^2 \quad (24)$$

By solving above equation, we get [8]

$$V_r = \frac{-2 M_c V_i + \sqrt{4M_c^2 V_i^2 - 4 (M_c + 8 M_p) [(M_c - 8 M_p) V_i^2 + 16 E_o']}}{2 (M_c + 8 M_p)} \quad (25)$$

At ballistic limit, $V_r = 0$,

$$V_{50} = \sqrt{\frac{16 E_o'}{(8 M_p - M_c)}} \quad (26)$$

Comparison of Analytical and Experimental Results

By using the proposed model, ballistic limit is calculated for RT, 60°C, 80°C and 120°C and compared with the experimental data in Table-2. The predicted ballistic velocity for RT sample is 87 m/s, which is 4.81 % more than the experimental value. For thermally exposed samples, the variation in predicted ballistic limit is within 15 % than the experimental value.

Figure 14 shows the percentage of energy absorbed by different mechanisms for the RT, 60°C, 80°C and 120°C samples. It is clearly seen that the minimum energy absorption is done by delamination. Where as, primary, secondary fibers failure, moving cone and shear plug formation are the major energy absorption mechanisms for high velocity impact.

Table-3 shows the comparison of average energy absorbed by the laminates experimentally and analytically. The predicted energy absorption is in good agreement with experimental values for all samples. Residual velocity vs. impact velocity is shown in Fig.15, 16, and 17 for RT, 80°C and 120°C samples respectively. These results have good match with the experimental results.

Table-2 : Comparison of Analytical Vs. Experimental Ballistic Velocity

Sample	Experimental Ballistic Limit, m/s	Analytical Ballistic Limit, m/s
Room Temperature	83.6	87
60°C Thermal Loading	74	84
80°C Thermal Loading	69	78
120°C Thermal Loading	62	71

Table-3 : Average Energy Absorbed Above Ballistic Limit

Sample	Experimental Energy Absorbed J	Analyatical Energy Absorbed J
RT	44	38.65
80°C	32	31.70
120°C	26	25.67

Conclusion

Carbon/epoxy laminates are used to study the after effect of thermal loading on ballistic performance. It is observed that

- In high velocity impact test, energy absorbed by the laminate increases up to ballistic limit and becomes constant with increase in impact velocity up to 115 m/s.
- The major energy absorption mechanism consists of primary fibers failure, secondary fibers deformation, matrix cracking, moving cone and shear plug.
- With increase in temperature of thermal loading from RT to 120ÉC, the energy absorption capacity and the ballistic limit of CFRP composite reduced by 40 % and 25 % respectively. Increase in exposure temperature promotes early perforation and shear plug formation.

An energy based mathematical model is used to predict the ballistic performance and the after effect of thermal loading on it. The predicted properties are in good agreement with the experimental results for room temperature and thermal loading sample.

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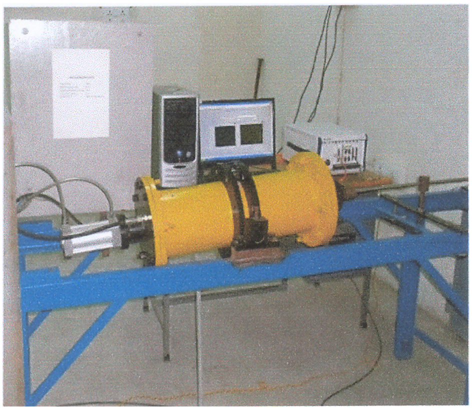

Fig.1 Impact Test Setup

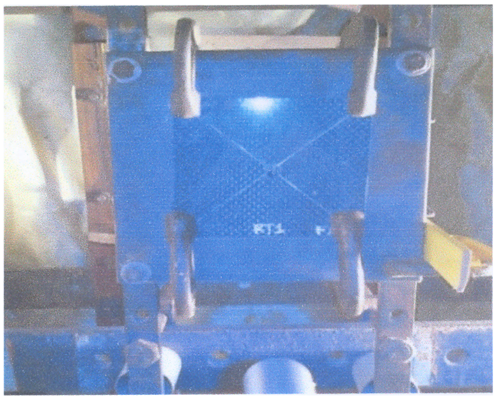

Fig.2 Clamping Condition

Fig.3 Impact Below Ballistic Limit for RT Sample

Fig.4 Embedded Condition of Bullet for 140°C Loading Sample

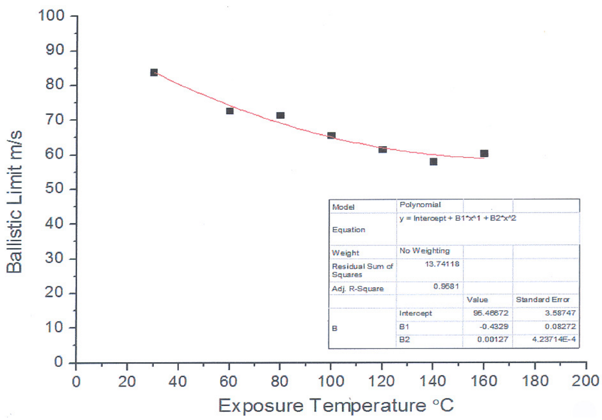

Fig.5 Ballistic Limit Vs. Loading Temperature

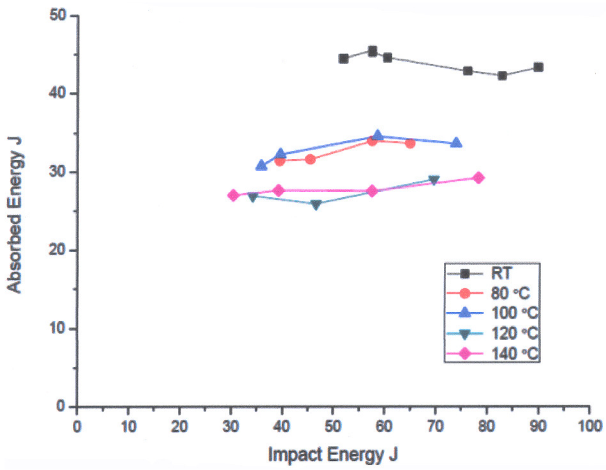

Fig.6 Impact Energy Vs. Energy Absorbed Above Ballistic Limit

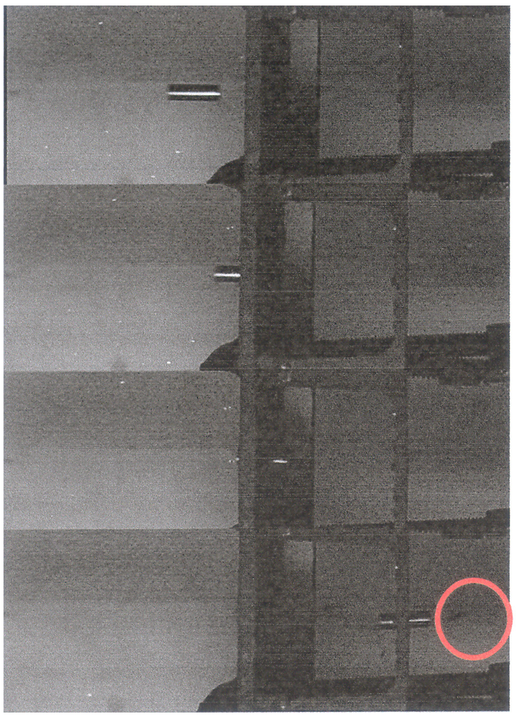

Fig.7 60°C Thermal Loading Sample for 24 h

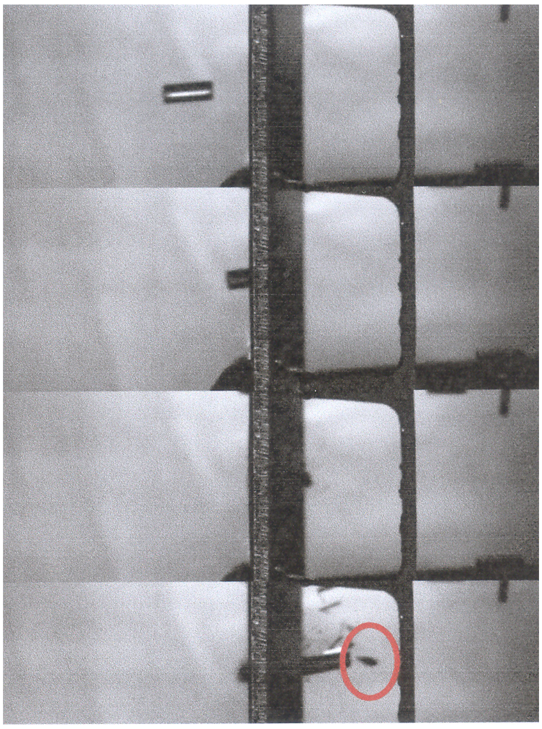

Fig.8 100°C Thermal Loading Sample for 24 h

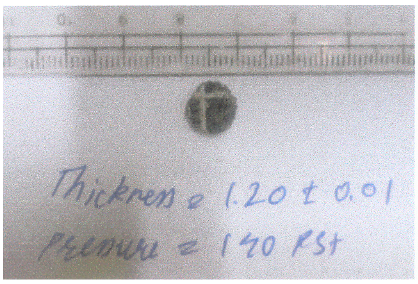

Fig.9 Shear Plug

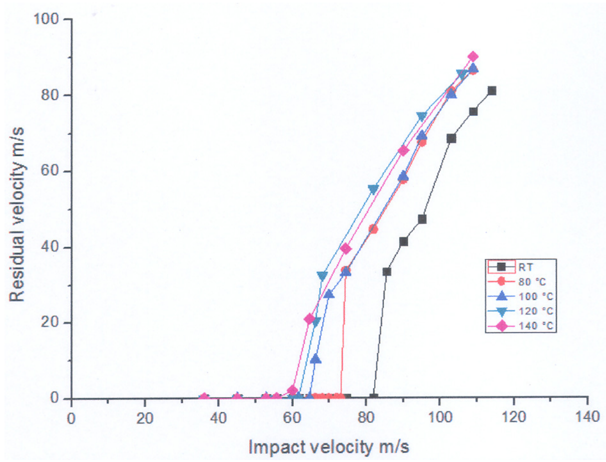

Fig.10 Impact Velocity Vs. Residual Velocity

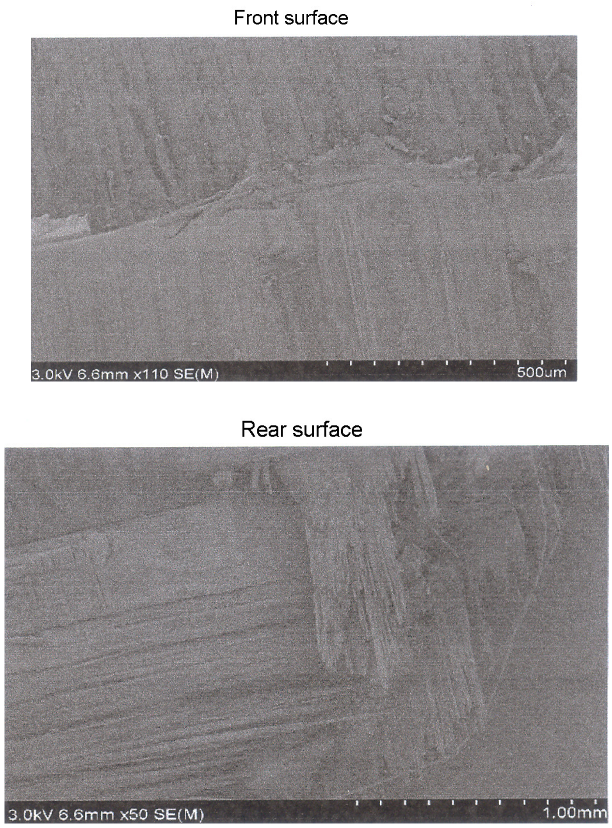

Fig.11 RT Samples Shear Plug

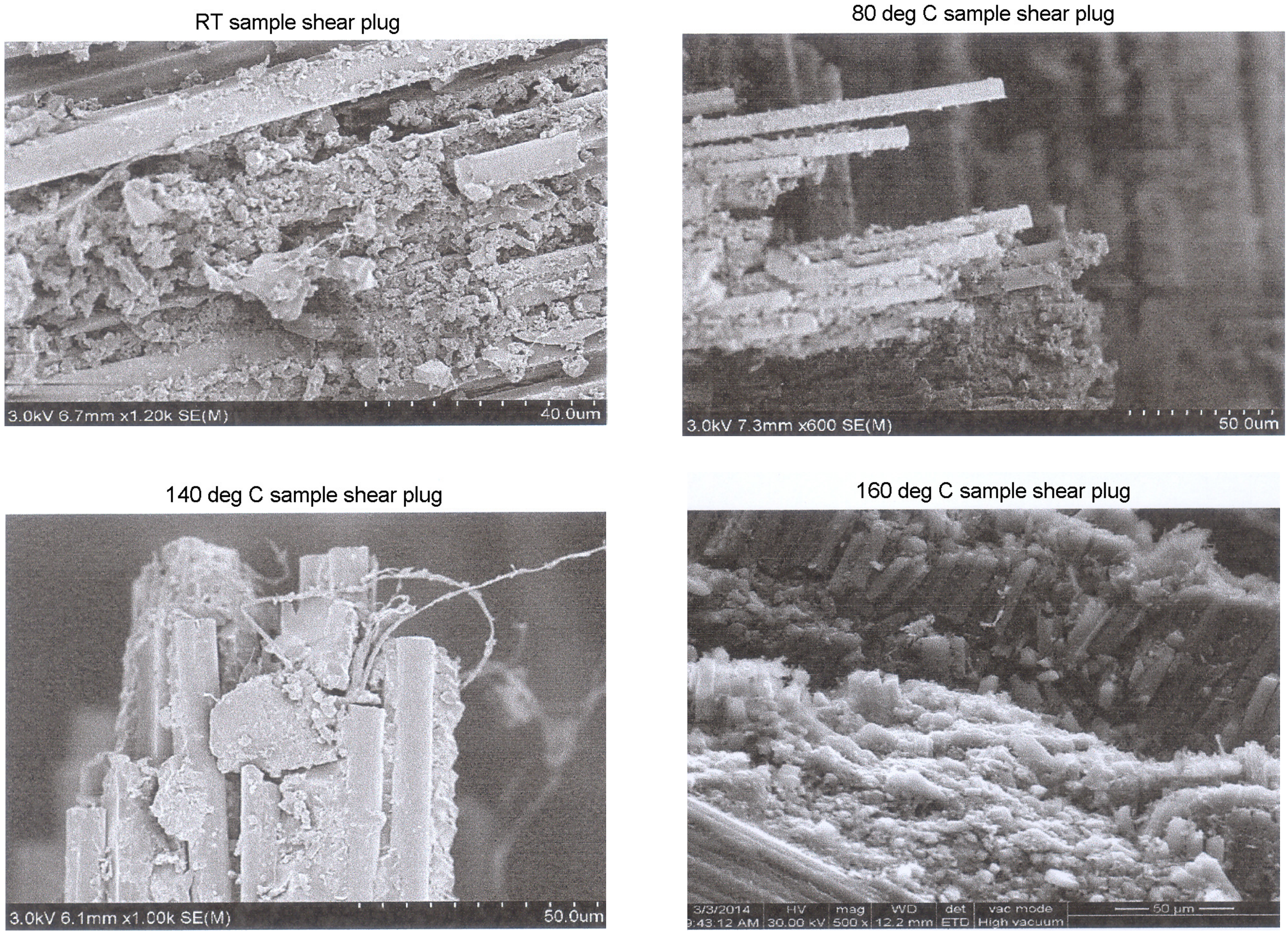

Fig.12 Rear Surface of RT 80°C, 140°C and 160°C Exposed Shear Plugs

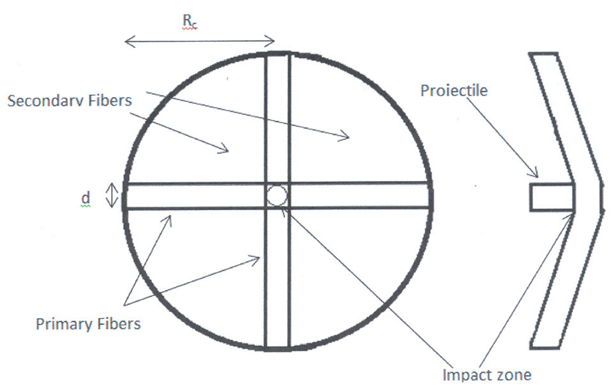

Fig.13 Primary and Secondary Fiber on Target

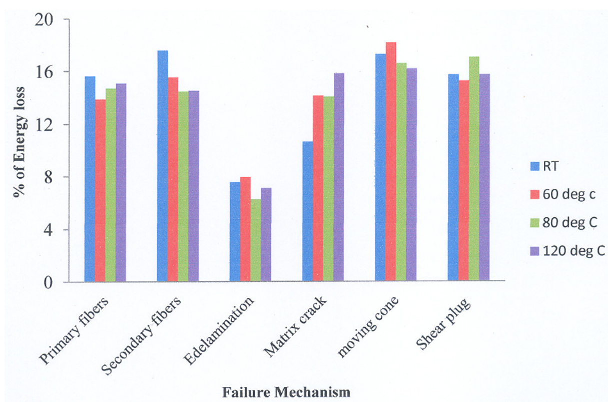

Fig.14 Percentage of Energy Dissipation in Various Failure Mechanisms

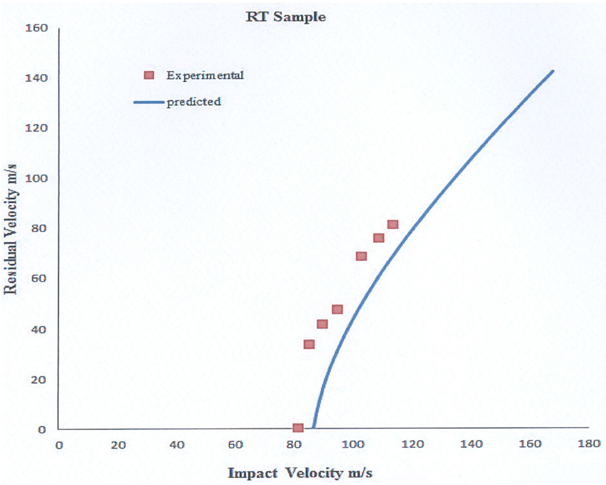

Fig.15 Impact Vs. Residual Velocity of Room Temperature Sample

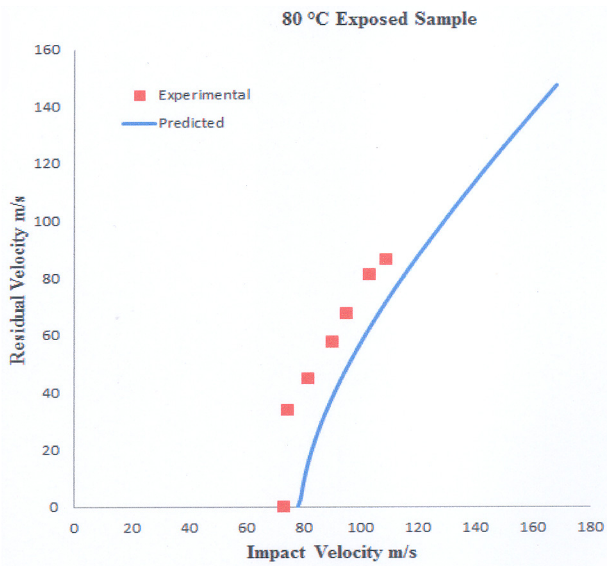

Fig.16 Impact Vs. Residual Velocity of 80°C Thermal Loading Sample

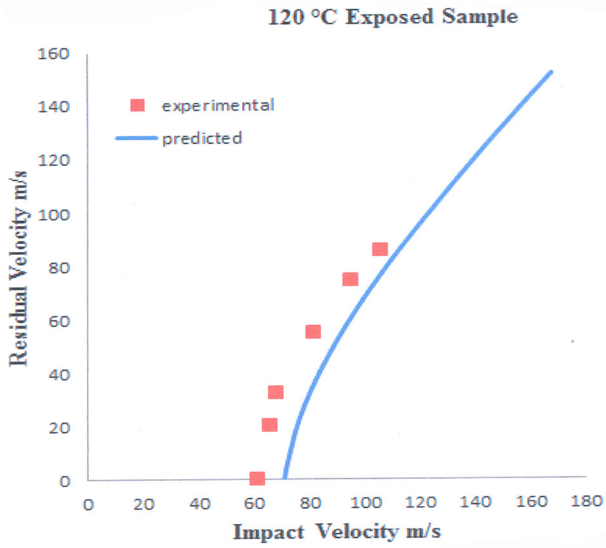

Fig.17 Impact Vs. Residual Velocity of 120°C Thermal Loading Sample