Effect of Moulding Pressure on High Strain Rate Performance of UHMWPE Composite

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Abstract. Resin starved fibre reinforced plastic (FRP) composites are very much in demand for defence applications. Based on the type of matrix, processing temperature for a given fibre-matrix system can be optimized. However, moulding pressure responsible for the consolidation of an FRP laminate may vary, which has to undergo a rate-dependent enactment in armour applications. The present study is focused on the high strain rate compressive stress-strain performance of Ultra-High-Molecular-Weight-Polyethylene (UHMWPE) fibre-based composite. UHMWPE laminates were moulded at two different pressures of 34.5 bar and 138 bar, respectively. Cylindrical specimens having ~0.5 aspect ratio and areal density of 4.01 kg/m^2 were cut-out and tested under high strain rate compressive loading. Test results of high strain rate loading revealed that increasing moulding pressure by four times enhanced the peak stress by 33% and the strain by 22%. Higher pressure moulded composites attained an 11% higher strain rate as well. Damage studies revealed relatively less damage to composite specimens as a function of higher compression moulding pressure. The study confirms that the mechanical performance of UHMWPE composites can be enhanced by increasing the moulding pressure, but to what limit, remains a mystery.

1. INTRODUCTION

Nowadays, ultra-high molecular weight polyethylene (UHMWPE) composite materials are extensively used as a raw material for the personal body armour applications [1]. UHMWPE fibres have very high specific tensile strength and modulus, thus superior ballistic performance than any other fibre. The UHMWPE fibres are arranged in a polymeric matrix material to form a lamina which is then stacked as $(0/90)_2$ cross-ply fabric. This cross-ply fabric is cut according to the required dimensions and pressed in a compression moulding machine to form a laminated armour panel.

The mechanical response of UHMWPE fibre-reinforced composite materials is rate sensitive. Koh et al. [2] tested UHMWPE fibre-reinforced composites under tensile loading at high strain-rate. It was determined that as the strain-rate increases, failure strain decreases whereas strength increases. A similar trend was also observed when UHMWPE fibre reinforced composites were tested in a Split-Hopkinson Pressure Bar (SHPB) at strain-rates up to 1200 /s [3]. Shaker et al. [4] studied out-of-plane compression of UHMWPE fibre reinforced polymer composites at strain-rates up to 8000 /s and found that out-of-plane compressive strength was ~800 MPa. Liu et al. [5] studied the in-plane compressive response of UHMWPE fibre reinforced polymer composites at a high strain rate using SHPB and observed that peak strength increased at high strain rates.

It is a well-established fact that fabrication temperature and pressure play a vital role in determining the ballistic performance of UHMWPE fibre reinforced composite materials. Zeng et al. [6] fabricated composite laminates at different temperatures ranging from 80 - 120 ºC and noticed that laminates fabricated at higher temperatures had better ballistic resistance. A ballistic impact study was conducted on laminated armour panels fabricated from Dyneema® HB 26 at two different pressures of 165 bar and 300 bar [7]. It was observed that laminated armour panels fabricated at higher pressure provided better ballistic resistance. Lassig et al. [8] stated that consolidation pressure affects void density, cracking in the matrix, fibre volume fraction of composite and fibre-fibre bonded joints during compression moulding. They reported that increasing moulding pressure from 20 bar to 165 bar resulted in ballistic resistance enhancement by 5.31% and further higher pressure of 300 bar could only improve ballistic resistance by 0.27%. This indicates that there could be some critical limit of moulding pressure.

It is evident from the known literature that the moulding pressure does play a vital role in establishing the high strain rate performance of UHMWPE fibre-reinforced composite materials. This study is conducted to evaluate the out-of-plane compressive high strain rate performance of UHMWPE

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fibre-reinforced composite materials. The composite laminates were fabricated using compression moulding technique at two different pressures. Out-of-plane dynamic compression tests were performed on an in-house developed split-Hokinson pressure bar (SHPB) apparatus. The contrast between out-of-plane compressive strength and stress-strain response of UHMWPE fibre-reinforced composites fabricated at different pressure was studied.

2. EXPERIMENTS

2.1 Materials and Specimen

UHMWPE composite laminates were fabricated by compression moulding of 16 layers of a commercial grade of UHMWPE lamina. The commercial UHMWPE grade used for the laminate fabrication was Spectra Shield SR-3124, by Honeywell Inc., USA. Each layer of SR-3124 comprises of four unidirectional plies of UHMWPE laid orthogonal to each other. Compression moulding was performed at a temperature of 115 ^{0}C (240 F). The two different pressures selected for the study were 34.5 bar (500 psi) and 138 bar (2000 psi), respectively. The higher pressure for compression moulding is four-fold the lower pressure for a clear difference in properties as a function of moulding pressure. The moulded composites had an areal density of 4.01 kg/m^2. Rota broach machining was used to cut out 10mm diameter cylindrical specimens from the composite laminate. The cut-out specimen had the desired aspect ratio of in the range of 0.45 - 0.5 [9].

2.2 Split-Hopkinson pressure bar test

High strain rate testing in the thickness direction of the compression moulded composite specimens was performed using SHPB apparatus developed in-house at the Indian Institute of Technology Delhi, India. The SHPB set-up typically comprises of three Titanium (Ti6Al4V) bars of 16 mm diameter. The bars used in set-up were, a striker bar of length 240 mm, an incident bar of length 1200 mm and a transmission bar of length 1200 mm, respectively. The Titanium grade used for bars had a density of 4430 kg/m^3 and Young's modulus of 113.8 GPa and elastic wave speed in the bar material is 5068 m/s. It may be noted that the modulus of bar material had to be significantly higher than that of material being tested so that the bars remain within the elastic limit through-out the test. Also, to avoid severe impedance mismatch between the bars and specimen materials, high-density metals like steel should be avoided while testing low-density composites. To obtain the acceptable dynamic equilibrium in the SHPB test a pulse shaper having a thickness of 1.4 mm and 3.1 mm diameter was used between the striker bar and the incident bar. A commercial-grade of natural rubber (Linatex) was used to serve the purpose of the pulse shaper. The schematic of the SHPB set-up is shown in Figure 1.

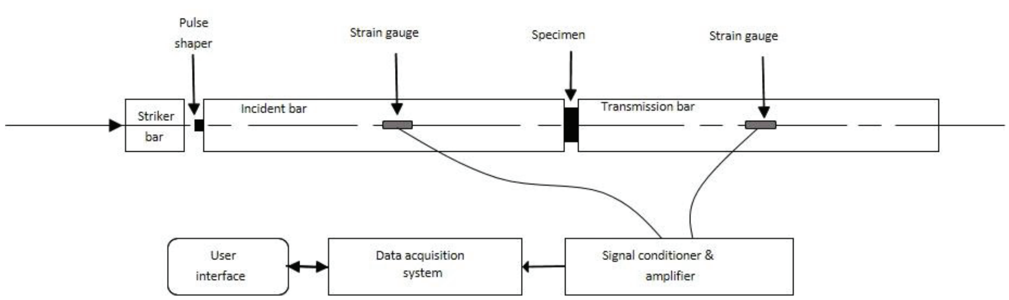

Figure 1. Schematic set-up of compressive split Hopkinson pressure bar

The composite specimen is placed in between the incident and transmission bar for the compressive high strain rate testing. The striker bar is accelerated by Nitrogen gas pressure acting on the striker bar. After travelling for a distance of 2000mm in a steel barrel, the striker bar hits the pulse shaper placed on the incident bar using a suitable lubricant for minimum friction condition. The impact of striker produces a compressive elastic wave in the incident bar, which travels through the incident bar as a function of density and velocity of sound of the bar material. When this incident wave crosses the mid-section of the incident bar, strain induced in the bar is recorded in the form of voltage change as a function of change in the resistance of strain gauge. On reaching the end of the incident bar, a part of the incident wave is reflected as a tensile wave and the rest of the elastic stress wave passes through the specimen and enters the transmission bar as a compressive wave. The resulting reflected and transmitted waves

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in-turn produce reflection and transmission strain in the respective strain gauges. The voltage signals received from the incident bar in the form of reflection are responsible for the determination of specimen strain and strain rate. The voltage change recorded from the strain gauge mounted on the transmission bar is used to estimate specimen stress. A suitable signal conditioner amplifier is used to power up 350 Ω strain gauge, using 2 volts input. The data acquisition system records voltage variation at a rate of 2 Mega samples per second (Msps). Compressive high strain rate properties of composite specimens including stress (σ), strain (ε) and strain rate ($\dot{\varepsilon}$) were calculated based on one-dimensional propagation of elastic wave as discussed in the known literature using the following equations [10]:

$$\text{The strain rate, } \dot{\varepsilon}_s(t) = \left(\frac{2C_0}{Ls}\right) \varepsilon_r(t) \tag{1}$$

$$\text{The average strain, } \varepsilon_s(t) = \pm\left(\frac{2C_e}{Ls}\right) \int_0^t \varepsilon_r(t).\, dt \tag{2}$$

$$\text{The average stress, } \sigma(t) = \pm E \frac{A_B}{A_S} \varepsilon_t(t) \tag{3}$$

where A_B is the cross-sectional area of the bar, A_S is the cross-sectional area of the specimen, E is the modulus of elasticity of the bar material, C_e is the wave velocity in the bar, L_S is the length of the specimen, $\varepsilon_r(t)$ is the reflected strain gauge signal and $\varepsilon_t(t)$ is the transmitted strain gauge signal.

For the estimation of strain rate induced in the specimen slope of strain rate-time curve serves the purpose well for homogenous isotropic materials. However, in the case of fibre reinforced composites stress wave attenuation is an inevitable phenomenon; as a result dynamic equilibrium attainment is generally not possible [11]. For such cases, the scheme suggested in the known literature for materials showing stress wave attenuation is useful. The strain rate in this work is calculated by "dividing the area under the strain rate-strain curve, up to maximum strain under loading, by the maximum strain" [12].

3. RESULTS AND DISCUSSION

Through-the-thickness dynamic compression tests were performed on 16 layered UHMWPE composite compression moulded at low (34.5 bar) and high (138 bar) pressure. Nitrogen gas pressure used for propelling the striker bar was in the range of 0.5 – 3.0 bar. The resulting strain rates attained by the UHMWPE specimens were in the range of 2100 – 4770 /s, respectively. The maximum stress value of the stress-strain response before softening was considered as the peak stress; similarly, the strain was considered until it reaches maxima. The toughness was obtained by measuring the area under the stress-strain response curve.

3.1 High strain rate stress-strain response

Dynamic compression responses of low and high pressure moulded UHMWPE composites are shown in Fig. 2. The difference in rate-dependent behavior of low and high pressure moulded UHMWPE composites is evident from Fig. 2. For both the composites small initial section of the linear elastic region was followed by a relatively larger non-linear elastic stress growth. The stress-strain curve revealed a near plateau region after acquiring a stress value close to the peak for a given rate of loading. After acquiring the peak stress, the behavior of low and high pressure moulded composite differed significantly. However, after attaining the peak stress, the variation in the form of dropping stress in case of low pressure moulded specimens and rising stress in case of high pressure moulded specimens is noticeable, for intermediate loading rates. Further higher loading rates resulted in peak performance of both the composites, which was followed by macroscopic damage in the form of delamination. Nevertheless, it may be noted that the increasing rate of loading had barely any effect on the total strain induced in the low pressure moulded specimens. The low pressure moulded specimens attained the peak strain quite fast when the strain rate exceeded 3000/s and the total strain was in the range of ~0.27. On the contrary, high pressure moulded composites exposed a continuously rising total strain trend as a function of rising rates of loading, till the specimen macroscopically fractured at a strain of ~0.33. Thus, revealing the fact that increasing moulding pressure by four times has enhanced the total strain by 22%.

Figure 2 (a) depicts the identical rising stress-strain curve for low pressure moulded specimens, when impacted due to Nitrogen gas pressure in the range of 0.5 – 1.5 bar, respectively. At low Nitrogen gas pressure of 0.5 bar, a low strain rate of 2105 /s was induced in UHMWPE specimen. The resulting

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specimen was physically intact with minimal damage. As the rate of loading increased, the composite exposed enhanced rate-dependent properties, until the gas pressure reached 1.2 bar pressure, resulting in a strain rate of 4050 /s. Associated with this growth in performance was slightly greater macroscopic damage on the cylindrical surface, but all the specimens till 4050/s rate of loading were physically intact. The further higher loading rate of 4220 /s, induced due to Nitrogen gas pressure of 1.5 bar resulted in a macroscopic failure of low pressure moulded specimen. The UHMWPE composite failure was noted in the form of delamination into two pieces. Also, the composite experienced the highest stress, strain and strain rate for these delaminated specimens.

Figure 2 (b) shows the rate-dependent behavior of high pressure moulded UHMWPE composites. Similar to low pressure moulded composite specimens, high pressure moulded composite specimens also revealed rising stress-strain behavior as a function of rising rates of loading. However, the slope of the stress-strain curve improved significantly. The strain rates attained by the high pressure moulded composite specimens were significantly lower for a given Nitrogen gas pressure when compared to low pressure moulded specimens. At a gas pressure of 1.5 bar, whereas low pressure moulded specimen delaminated at a strain rate of 4220 /s, the high pressure moulded specimens attained strain rate in the range of 3400 – 3500 /s, without significant damage.

Interestingly, increasing moulding pressure by four times enhanced the high strain rate performance of UHMWPE composite. At a strain rate of 4650 /s, composite exposed peak performance without delamination at a gas pressure of 2.5 bar. The further higher gas pressure of 3.0 bar resulted in the delamination of composite specimens identical to low pressure moulded specimen. However, the peak stress attained by the delaminated specimen was 595 MPa at a peak strain of 0.33, which is much higher than the intact specimen peak stress of 521 MPa at a peak strain of 0.32.

Though both the composites were derived from a single material system, the variation of a single parameter in the manufacturing cycle has significantly enhanced the properties of the resulting composite. Increasing compression moulding pressure by four times has resulted in just doubled gas pressure requirement for the successful damage of composites, depicted in the form of delamination in this case for high pressure moulded specimens. Whereas low pressure moulded composite resulted in constant peak strain, the high pressure moulded composite depicted constantly rising peak strain which in-turn will help in enhancing the area under stress-strain curve responsible for higher energy handling capacity of the composite material. An increment in peak stress by 33% and peak strain by 22% is a clear indicator of properties enhancement as a function of increasing moulding pressure.

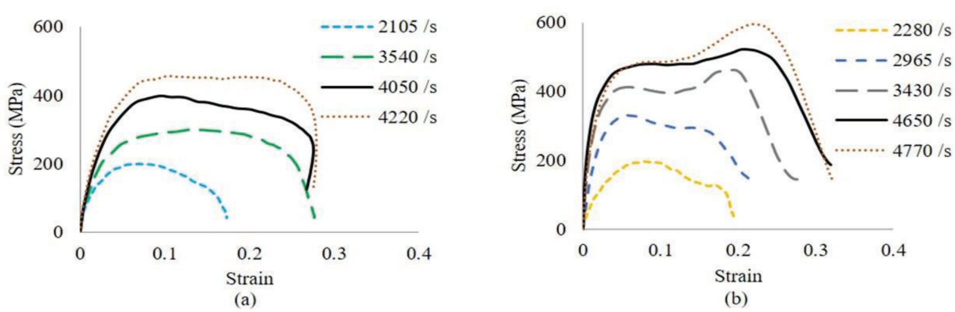

Figure 2. Dynamic stress-strain performance of composites moulded at (a) 34.5 bar and (b) 138 bar

3.2 Comparison of high strain rate response of low and high pressure moulded composites

The dynamic stress-strain responses of low pressure (LP) and high pressure (HP) compression moulded composites for identical incident energy and identical damage is shown in Figure 3. For identical Nitrogen gas pressure of 1.5 bar, a significant difference in the non-linear elastic stress growth was depicted, as shown in Figure 3 (a). The LP moulded composites attained peak stress, which was followed by a plateau until the decay of stress at constant strain. It may be noted that the LP moulded specimen delaminated at the loading rate of 4220/s. In the case of HP moulded specimen, the higher non-linear elastic modulus was followed by a secondary rise of the stress curve after a strain of 0.1. This peculiar phenomenon of minor stress reduction followed by a rise in the stress may be attributed to higher moulding pressure. High moulding pressure aids in better consolidation of plies due to the embedding of fibres in the adjacent plies in the resin starved laminate. HP moulding resulted in an intact specimen with a higher slope of the non-linear elastic stress-strain curve, lower strain rate, lower strain and identical peak stress as that of LP specimen.

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Figure 3(b) depicts the dynamic stress-strain plots of LP and HP moulded specimen at the strain rate resulting in the physical breakdown of the composite specimen. Nitrogen gas pressure required to propel striker bar for the delamination of HP moulded specimen just doubled from 1.5 bar to 3.0 bar. The rate of stress growth improved significantly and the plateau region followed by a secondary rise in stress was much higher for HP moulded specimen. Associated with the higher impact energy is the enhanced performance of HP moulded composite, depicted in the form of higher dynamic modulus, higher peak stress and higher total strain to failure, resulting in higher material energy handling capacity.

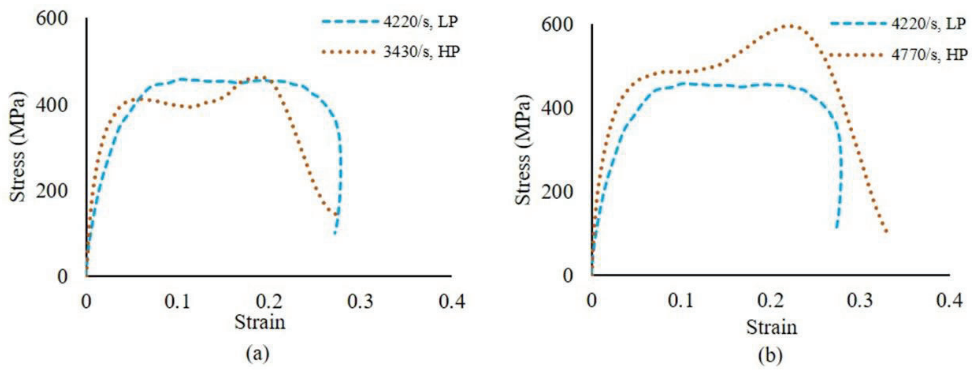

Figure 3. Dynamic stress-strain response comparison, (a) at identical impacting load, (b) at loading rate resulting in delamination

3.3. Influence of strain rate on dynamic properties

From the above dynamic stress-strain response of LP and HP moulded UHMWPE composites it is evident that there is a dependency of material properties on the moulding pressure and rate of loading. Therefore, the sensitivity of dynamic properties including peak stress, peak strain and toughness with respect to strain rate is discussed in this section for LP and HP moulded composites. Figure 4 depicts the influence of strain rate on the dynamic compressive properties of LP and HP moulded UHMWPE composites. The peak stress enhanced with the increment of strain rate in a linear fashion, as shown in Figure 4 (a). The peak stress of HP moulded composite always remained higher as compared to LP moulded composite. The relationship between the stress and strain rate for LP and HP moulded composites can be linearly established using Equation 4 and 5. An increment of 22.5% in the slope of the stress-strain rate curve for HP moulded composite is a clear indicator of property enhancement as a function of moulding pressure. Within the strain rate regime of 2100 – 4220/s for LP moulding and 2280 – 4770/s for HP moulding, the percentage increment in the stress with respect to strain rate was 128.2% and 201.3%, respectively. Thus, confirming the rate-dependent performance of UHMWPE composites.

LP moulded: $\text{Stress} = 0.1166\dot{\varepsilon} - 69.142 \ (R^2 = 0.9656)$ (4)

HP moulded: $\text{Stress} = 0.1422\dot{\varepsilon} - 99.736 \ (R^2 = 0.9552)$ (5)

Figure 4 (b) depicts the linear increment in the peak strain as a function of strain rate. Although, both the LP and HP moulded composites comprises an identical number of UHMWPE layers, a significant difference in terms of total maximum strain attained and slope of increment of strain is observed. Healthy rise in peak strain is a clear indicator of the deformation of composite, which in turn will also govern the area under the stress-strain curve. The percent increment in the peak strain of LP and HP moulded composites within the experimental range of strain rate is 60.8% and 90.2%, respectively. The relationship between the strain and strain rate for LP and HP moulded composite can be linearly estimated using Equation 6 and 7.

LP moulded: Peak strain = $5E\text{-}05\dot{\varepsilon} + 0.0755 \ (R^2 = 0.9651)$ (6)

HP moulded: Peak strain = $7E\text{-}05\dot{\varepsilon} + 0.0329 \ (R^2 = 0.9840)$ (7)

The toughness of HP moulded composites was slightly lower as compared to LP moulded composites at lower rates of loading. With an increase in strain rate above ~2900/s, the toughness of HP moulded composite took over the LP moulded composites. The increase in toughness within the strain

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rate regime was three and six times the initial toughness value for LP and HP moulded composites. An increment of 36% in toughness, due to enhancement of moulding pressure by four times is an indicator of better ballistic performance of an identical number of UHMWPE layers. Linear growth of toughness with respect to strain rate can be given using Equation 8 and 9, respectively.

LP moulded: $\text{Toughness} = 0.0363\dot{\varepsilon} - 50.188 \; (R^2 = 0.9664)$ (8)

HP moulded: $\text{Toughness} = 0.0519\dot{\varepsilon} - 92.429 \; (R^2 = 0.9849)$ (9)

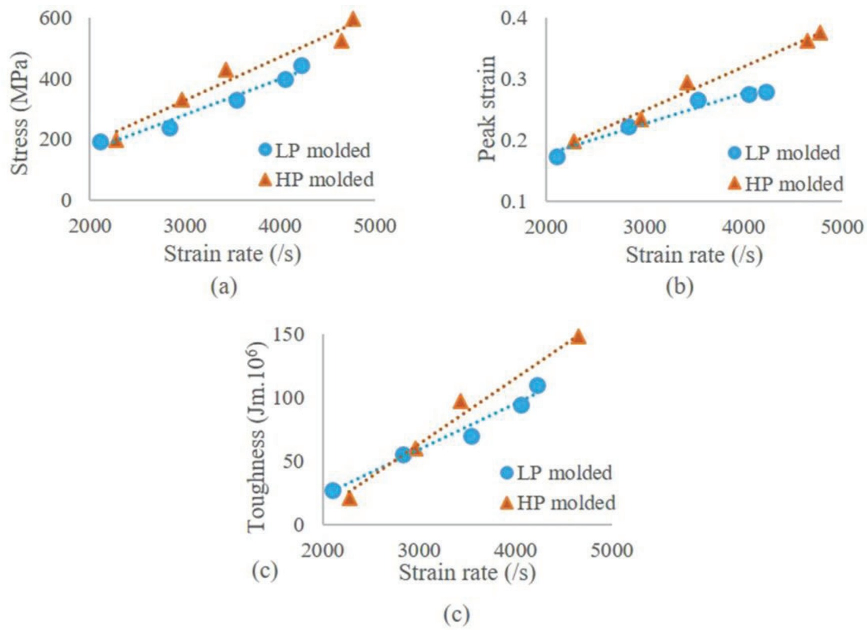

Figure 4. Effect of moulding pressure as a function of strain rate with respect to (a) peak stress, (b) peak strain, and (c) toughness

Figure 5 depicts the peak stress attained by the low and high pressure moulded UHMWPE composites at the first occurrence of macroscopic damage in the form of delamination. Peak stress improvement of 33% is recorded as a function of increment in the moulding pressure from 34.5 bar to 138 bar. Enhancement in peak stress, improved strain to failure and a higher rate of loading attained by high pressure moulded UHMWPE composites indicate the possibility of developing better ballistic resistant, lightweight UHMWPE composites without increasing the areal density of UHMWPE composites. Focused studies are required to establish the highest moulding pressure beyond which UHMWPE composite properties show no improvement or deterioration.

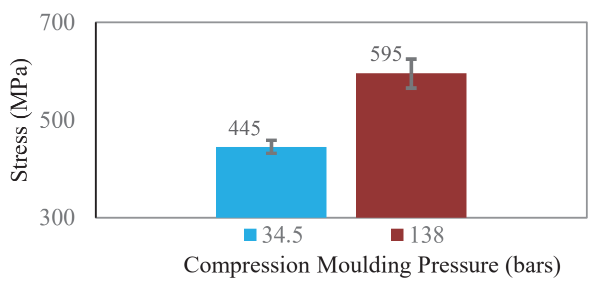

Figure 5. Effect of moulding pressure on peak stress of UHMWPE composite under dynamic loading

3.4. Macroscopic analysis

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Macroscopic images of LP and HP moulded UHMWPE composites after dynamic testing are shown in Figure 6. Low pressure moulded specimens when loaded at 2105/s strain rate resulted in relatively higher damage on the specimen surface in contact with the incident/transmission bar (Figure 6(a)), as compared to high pressure moulded specimen under identical dynamic load condition as depicted from Figure 6(d). Damage in the form of fibre pull-out, individual ply bending due to matrix dislodging may be noted from these intact specimens loaded at lower dynamic load conditions. Lower damage due to high moulding pressure under identical load conditions indicates that higher consolidation pressures can further enhance the dynamic properties of UHMWPE composites. At a strain rate of 4220/s, LP moulded specimen experienced delamination along with higher ply damage resulting in larger fibre bundles getting dislocated as shown in Figure 6(b). The delaminated surface of the LP moulded specimen revealed ply level damage in the form of fibre bundles bending and twisting. However, fibre failure sites are negligible as the low interlaminar shear strength of laminate allows delamination before the dynamic loading could break the high tenacity fibre as depicted in Figure 6(c). Figure 6(c) shows the delaminated surface of a specimen. Delamination of HP moulded specimen revealed higher damage in the form of twisted, bent and entangled fibres at a strain rate of 4770/s, as shown in Figure 6(e). The delaminated surface further confirmed higher damage, as more number of individual twisted and entangled fibres can be seen in Figure 6(f), as compared to Figure 6(c) of LP moulded specimen. Thus, confirming the fact that higher consolidation pressure helps in enhancing the interlaminar shear strength of UHMWPE composites.

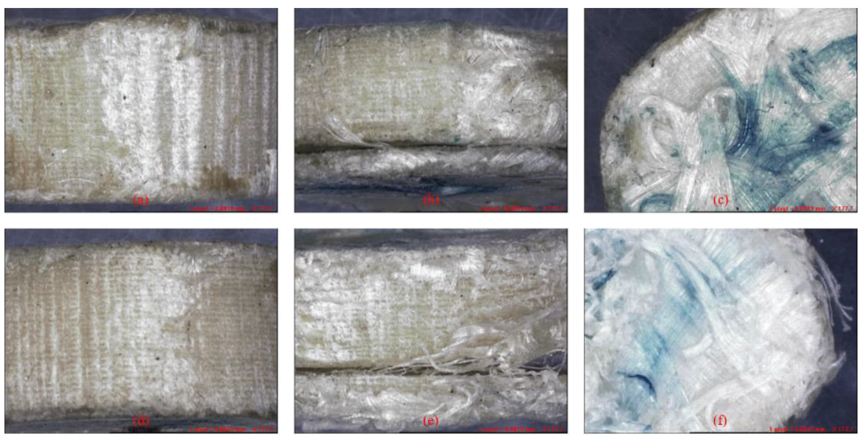

Figure 6. Macroscopic failure of UHMWPE composite tested at a strain rate of (a) 2105/s-low pressure moulded, (b) 4220/s-low pressure moulded, (c) delaminated surface at 4220/s of low pressure moulded, (d) 2280/s-high pressure moulded, (e) 4770/s-high pressure moulded, and (f) delaminated surface at 4770/s of high pressure moulded

4. CONCLUSIONS

Studies were carried out on low (34.5 bar) and high (138 bar) pressure compression moulded UHMWPE composites under high strain rate compressive loading. The high strain rate tests were conducted on SHPB apparatus in the thickness direction of composite laminates having an areal density of 4.01 kg/m2. The low and high pressure moulded composites were tested in the strain rate range of 2100 – 4220/s and 2280 – 4770/s, respectively. Based on high strain rate loading test results, it can be concluded that higher compression moulding pressures enhance the performance of UHMWPE composites. Following inferences can be made on the basis of presented experimental evaluations:

Irrespective of compression moulding pressure, the performance of UHMWPE composites enhances as a function of rising rates of loading.

For identical load conditions, composites moulded at higher pressure displays higher peak stress and the slope of the stress-strain curve improves as a function of rising moulding pressure.

The strain constantly grows with rising rates of loading in case of high pressure moulded composites. Low pressure moulded composites were easy to deform and a constant peak strain value of 0.27 was recorded for all the specimens loaded at strain rates above 3500/s.

Toughness was the only parameter that was recorded higher for low pressure moulded composites, at low rates of loading. With an increase in the strain rate above 2900/s, the toughness of high pressure moulded composites exceeded the toughness of low pressure moulded composites.

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The peak stress value increased by 33% for the successful macroscopic failure of the UHMWPE composite moulded at 138 bar pressure. Incrementing compression moulding pressure by four times enhanced all the major composite properties, indicating the need for further studies on higher pressure moulded UHMWPE composites.

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