DYNAMICAL COMPRESSIVE TESTS IN UHMWPE SAMPLES WITH DIFFERENT THICKNESS/DIAMETER RATIO

Dias, R.R.¹, Cardoso, A. L.V.¹, Pereira, I. M.¹*, Souza, S.D.², Patricio, P. S. O.²,  
1- Brazilian Army Technological Center, Brazil, Av. das Américas, 28705 - Barra de  
Guaratiba, Rio de Janeiro - RJ, 23020-470, rrodrigues083@gmail.com  
2- Federal Center of Technological Education of Minas Gerais, Belo Horizonte, MG.

ABSTRACT

Ultra-high molecular weight polyethylene samples were submitted to dynamical  
compressive test in a split Hopkinson Pressure Bar. Three thickness/diameter ratio  
(0.11, 0.44 and 0.64) and two strain rates (3250 s⁻¹ and 6500 s⁻¹) were used to  
understand how the test set-up influences the stress equilibrium and the constancy of  
strain rate during the impact. All studied samples achieved stress equilibrium, but the  
samples with smaller ratio achieved it more easily. Nevertheless, samples with the  
smallest ratio were not able to achieve strain rate constancy. The H/D = 0.11 samples  
presented an oscillatory behavior post-yield strength, which was related to the  
transmitted signal. Additionally, dynamical stress-strain curves were plotted and their  
behavior were investigate.

Keywords: high strain rate; split Hopkinson pressure bar; dynamical stress-strain  
curves, UHMWPE.

1 INTRODUCTION

Lightweight bulletproof vests and ballistic helmets are changing in order to  
become lighter, giving higher mobility to the warfighter¹,². To attend this demand  
thus, polymeric materials and polymeric matrix composites have been studied in  
applications associated with impact protection because of their good strength/weight  
ratio.³-⁵ Among the polymeric materials, ultra-high molecular weight polyethylene  
(UHMWPE) is receiving major attention. UHMWPE refers to polyethylene with  
average molecular weight above 10⁶ g/mol, typically ranging from 2.5×10⁶ to 6×10⁶  
g/mol, in which the longer molecular chains serve to spread the load of a ballistic  
impact more easily by strengthening intermolecular interactions what results in a very
tough material, with the highest impact strength of the thermoplastics presently conceived \(^{(6)}\).

Proper experiments to understand material behavior under dynamic loading at high strain rate need to be carefully designed \(^{(7)}\). The split-Hopkinson pressure bar (SHPB) is among the most reliable experiments. SHPB investigates the mechanical properties of samples submitted to high strain rates, between \(10^2 \, \text{s}^{-1}\) and \(10^4 \, \text{s}^{-1}\). The technique is commonly used for dynamic compression tests \(^{(8)}\). The equipment comprises two cylindrical bars, both made of the same material, having the same diameter and length. One is named the incident bar and the other, the transmission bar. Other components are the strike bar, which is a cylindrical bar of smaller length, a propulsion system and an electronic control interface for data acquisition and manipulation, Figure 1.

![Figure 1 - Isometric view of SHPB system \(^{(9)}\).](image)

Hopkinson test consists in firing the strike bar, with established impact velocity, \(v_{SB} \), through an instantaneous release of gas from the propulsion system, towards the free end of the incident bar. When that happens, a compressive loading pulse is generated. The pulse travels along the incident bar and reaches the sample on the other end of the bar. Part of the stress pulse reaches the transmission bar and part is reflected back to the incident bar. Strain gauges connected to both bars record the stress pulse signals, which are converted to voltage signals. Finally, the amplifier sends it to the digital oscilloscope to be recorded.

Variation of stress, \(\bar{\sigma}_s\), strain, \(\bar{\varepsilon}_s\), and the strain rate, \(\dot{\varepsilon}\), can be obtained from the recorded signals through Eq. (A) to (C) \(^{(7)}\):
where $E$ is the Young’s modulus of incident, transmission and strike bars, $A_s$ is the cross-section area of the sample, $A$ is the cross-section area of the bars, $C_b$ is the velocity of propagation of longitudinal waves in the bars and $L$ is the sample length. The incident, reflected and transmitted pulse amplitudes are, respectively, $\varepsilon_i$, $\varepsilon_r$ and $\varepsilon_t$.

### 2 MATERIALS AND METHODS

#### 2.1 Sample preparation

UHMWPE, commercialized as UTEC 3041, ($M_w = 3 \times 10^5$ g.mol$^{-1}$), was obtained from Braskem® (RJ, Brazil). Cylindrical shaped specimens were produced by mixing the pellets followed by hot pressing (AROTEC®) of 150 kgf at 200°C during 10 min. As the Hopkinson bars experiment requires flat interfaces$^{10}$ care was taken to obtain parallel smooth surface specimens. Before the tests, samples were heat treated at 110°C, during 24 hours (VENTICELL® furnace, MMM-Group™). In order to freeze the microstructure and to assure its homogeneity, all samples were cooled down on ice water.

#### 2.2 Dynamic compressive test

The dynamic compressive tests were performed in SHPB (REL, Inc®.), using cylindrical specimens. To minimize the impedance mismatch between bar and sample and, consequently, to increase the amplitude of the transmitted signal$^{11}$, the incident, transmission and strike bar were made of 7075-T6 aluminum alloy, with yield strength, $\sigma_{yield}$, of 380 MPa and $E = 69$ GPa. Three different thickness/diameter
(H/D) ratios were studied: 0.11, 0.44 and 0.64. They represent, respectively, H/D: 1.59/15, 3.3/7.5 and 6.4/10.

Both incident and transmission bar had 2000 mm length and 19.05 mm diameter. The strike bar had the same diameter and 203.2 mm length. To minimize the interfacial friction and, therefore, ensure that only one-dimensional mechanical waves propagate through the specimen \(^{(12)}\), a lubricant, 100% pure petroleum jelly, was used at the bar/sample interfaces in all experiments. Two different strain rate, \(\dot{\varepsilon}\), were investigated: 6500 s\(^{-1}\) and 3250 s\(^{-1}\).

At \(\dot{\varepsilon} = 6500 \text{ s}^{-1}\), H/D = 0.11 specimens were impacted with \(v_{SB} = 18 \pm 3.8 \text{ m/s}\) and H/D = 0.44 specimens were tested at \(v_{SB} = 21 \pm 1.4 \text{ m/s}\). On the other hand, at \(\dot{\varepsilon} = 3250 \text{ s}^{-1}\), H/D = 0.44 specimens were impacted with \(v_{SB} = 11 \pm 2.5 \text{ m/s}\) and H/D = 0.64 specimens were compressed with \(v_{SB} = 24 \pm 2.5 \text{ m/s}\). Results represent the average of four samples.

3 RESULTS AND DISCUSSIONS

3.1 Incident Wave

Figure 2(a) presents the incident wave measured at different test conditions. The incident wave shown in Figure 2(a) has a rectangular shape with a sharp rising edge and some oscillation. Trapezoidal incident pulses have been traditionally recognized as ideal for SHPB. The oscillations are due to the dispersion of the compression wave in different wavelengths traveling at different speeds. These oscillations have been named Pochhammer-Chree oscillations and they exist in the waves and curves obtained by SHPB \(^{(8)}\).

As seen in Eq. (C), the strain rate depends on: (i) the velocity of the sound waves travelling in the bar, (ii) the thickness of the samples and (iii) the amplitude of the incident, reflected and transmitted pulses.

The incident pulse is associated to the bar, while the reflected and transmitted pulses are correlated to the sample. The incident pulse is generated from the impact of the strike bar and it is acquired by the strain gage placed on the incident bar. \(\varepsilon_i\),
will, therefore, have bigger amplitude if the pressure (and consequently the velocity) used in the strike bar is higher. Nevertheless, it is possible to observe in Figure 2(a and b) that the higher incident pulse not necessarily generates the higher strain rates.

Figure 2 – Average incident wave measured by strain gages in the middle of the incident bar at different test conditions.

H/D = 0.44 and H/D = 0.64 samples, were both submitted to a strain rate of 3250 s\(^{-1}\). The first one achieved the smallest electric potential, while the second one achieved the highest one, Figure 2(a and b). These pulses outcome, respectively, in the smallest and the highest impact energies. Although, the two samples received very different incident pulses, both have the same average strain rate because the sample thickness (see Eq (C)) distributes the entire result.

3.2 **Reflected and Transmitted Wave**

The stress waves presented in Figure 2(a) describe the incident pulse. Figure 3 shows its reflection, described as the reflected wave (black line, left axis). The reflected pulse is generated by the mechanical waves that propagate through the incident bar, reach the sample and propagate back. Both pulses, incident and reflected, are recorded by the same strain gage, located in the middle of the incident bar. Both incident and reflected pulses contain high frequency oscillations \(^7\). That happens because, although one-dimensional wave propagation is assumed to occur during the test, strictly speaking, wave propagation in cylindrical bars is three-dimensional in nature, meaning that both axial and radial stress waves travel along the bar \(^10,13\).
Part of the incident pulse propagates through the samples and generates the transmitted pulse (Figure 3, red line, right axis), which is captured by the strain gage placed in the middle of the transmitted bar, Figure 4. If the specimen is made from ductile material, as observed in Figure 3(a to c), the transmitted pulse is not as dispersive as the incident and reflected pulses because the specimen acts as a filter.

For the UHMWPE samples, it is observed that the incident pulse i.e., $E_{\text{inc}}$, controls the intensity of the reflected pulse. Nevertheless, the geometry of the samples may also play an important role on the reflected wave. Figure 3(a to c), shows that the transmitted pulse signal, lasts, at least, four times the reflected pulses. Commonly, reflected and transmitted pulses last the same time period $^{(10)}$.

The transmitted pulses of the UHMWPE samples also maintain a trapezoidal form, except that of the H/D = 0.11 samples. This group of samples shows high frequency oscillation in the transmitted pulse, which may overthrow the dynamical stress-strain curve (see Figure 8). Therefore, it can be concluded that the small thickness/diameter ratio of the H/D = 0.11 samples was not sufficient to filter the signal generated by this specific impact, allowing a more dispersive transmitted pulse.

![Figure 3](image)

**Figure 3** - Reflected and transmitted pulses of the four groups of samples used.
Moreover, note that the H/D=0.44 group submitted to the same strain rate than the H/D=0.11 group presented a trapezoidal and less dispersive transmitted signal, suggesting that this geometry is more accurate to this energy of impact. Yet, comparing both groups of H/D = 0.44 specimens, it is possible to conclude, that the transmitted signal shape is also dependent on the strain rate. The transmitted pulse in Figure 3(c) is closer to a trapezoidal form than the one submitted to the higher strain rate, Figure 3(a), suggesting that for each geometry there is a strain rate threshold, above which the transmitted signals start to lose quality (14).

3.3 Stress Equilibrium

Equations (A), (B) and (C) represent, respectively, the average stress, $\bar{\sigma}$, average strain, $\bar{\varepsilon}$, and the strain rate, $\dot{\varepsilon}$. These average values represent useful material properties if the stress equilibrium exists in the specimen (15). When it occurs, the tension at the bar/sample interface is equal to the tension at the sample/bar interface. Therefore, Eq. D is valid (15):

$$\varepsilon_t = \varepsilon_R + \varepsilon_I$$  \hspace{1cm} (D)

If the stress equilibrium is achieved Eq. (A) to (C) can be reduced, as described at Eq. (E) to (G) (15):

$$\sigma_s = \frac{E_A}{A_s} \varepsilon_I$$  \hspace{1cm} (E)

$$\varepsilon_s = -\frac{2c_8}{L} \int_0^L \varepsilon_R \, dt$$  \hspace{1cm} (F)

$$\dot{\varepsilon} = -\frac{2c_8}{L} \varepsilon_R$$  \hspace{1cm} (G)

A useful tool to investigate the stress equilibrium is the “Force vs. Time” plots (16). According to this technique, the data obtained from the strain gage mounted on the incident bar records the force applied on the bar/sample interface, i.e. the incident force, $F_i$. Additionally, the strain gage mounted on the transmission bar registers the force applied on the sample/bar interface, transmission force, $F_t$. $F_i$ and $F_t$ are, therefore, correlated Figure 4).
The stress equilibrium is assumed to be achieved when the two curves converge to a common area. Thus, Eq. (E) to (G) undergo a reasonable simplification. Figure 5 shows the Force vs. Time plots of the studied specimens, deformed at $\dot{\varepsilon} = 6500 \text{ s}^{-1}$, Figure 5(a), and $\dot{\varepsilon} = 3250 \text{ s}^{-1}$, Figure 5(b).

**Figure 4 – SHPB testing technique representation.**

Figure 5 shows an initiation stage at $t_i \leq 20 \mu s$ and a propagation stage after 20 µs. During the propagation stage, a maximum of delta force, $\Delta F_{I-T}^{Max}$ is observed. In this study, the $\Delta F_{I-T}^{Max}$ is obtained according to Eq. (H).

$$\Delta F_{I-T}^{Max} = F_{I}^{Max} - F_{T}^{Min}$$  \hspace{1cm} (H)

Figure 5(a) shows that, during the propagation stage, despite $\Delta F_{I-T}^{Max} = 17 \text{ kN}$, observed for both samples, the equilibrium was achieved. $F_I$ and $F_T$ of both samples, nearly converge throughout the entire loading history. As observed for H/D = 0.11 specimen, $F_T$ and $F_I$ increase during the deformation process so strain hardening is observed only for the thinnest specimen.

**Figure 5 – Force vs. Time plots: (a) $\dot{\varepsilon} = 6500 \text{ s}^{-1}$ and (b) $\dot{\varepsilon} = 3250 \text{ s}^{-1}$.**
In Figure 5(b), when $t_i \leq 20\ \mu$s, both specimens present $\Delta F_{i-T}^{Max} > 13\ \text{kN}$. Nevertheless, during the propagation stage, $F_j$ of $H/D = 0.44$ samples behaves more steadily than $H/D = 0.64$ samples, thus $\Delta F_{i-T}^{Max}$ of 0.44 ratio decreased and the average standard deviation is smaller.

For better visualization, Figure 6 presents $H/D = 0.44$ specimen deformed, respectively, at $\dot{\varepsilon} = 6500\ \text{s}^{-1}$ and $\dot{\varepsilon} = 3250\ \text{s}^{-1}$. The plots are different, in shape and in value, mainly in the propagation stage. For both test conditions, at $t_i \leq 20\ \mu$s, $\Delta F_{i-T \text{average}}^{Max} = 17\ \text{kN}$. However, considerable difference is observed on $F_i$ after the propagation stage, where the samples submitted to smaller strain rate converge more easily than those submitted to higher strain rate. Nevertheless, for both conditions, at $t_i > 20\ \mu$s, the rear forces behave more evenly and during the entire propagation stage.

Observing Figure 5 and Figure 6, it is possible to state that not only $H/D$ ratio has considerable influence on the stress equilibrium during the experiment but also the strain rate, suggesting that for any sample ratio there is an $E_{\text{threshold}}$.

![Figure 6 - Force vs. Time for H/D = 0.44 specimen: (a) $\dot{\varepsilon} = 6500\ \text{s}^{-1}$ and (b) $\dot{\varepsilon} = 3250\ \text{s}^{-1}$](image)

**3.2 Strain rate behavior**

Another important point to be checked concerning the conditions of the experiment is the constancy of the strain rate. One of the main functions of the split
Hopkinson pressure bar is to obtain several stress-strain curves of a material under the same strain rate, in order to study the material dynamical properties under these conditions. Therefore, for each stress-strain curve, the strain rate must be constant. During an experiment, the strain rate in the specimen is initially zero, taking a finite amount of time for the specimen to reach a certain value of strain rate. After this rising time, a plateau is established at the plot “Strain rate vs Strain”, corresponding to constant strain rate along sample deformation.

Figure 7 shows the plots “Strain rate vs Strain” of the tested samples. The horizontal dashed red line represents the average strain rate obtained. All the groups, except the 0.11 ratio group achieved a plateau with constant strain rate. It is possible to see that, in this case, the strain rate decreases during deformation.

3.3 Dynamical stress-strain curves

Figure 8 shows the dynamic stress-strain curves of the samples. UHMWPE exhibits significant strain-hardening, which is clear by the continuous enhancement of the stress after yield. The behavior is observed regardless the applied test condition. We can observe that the deformation at the ultimate compression strength is bigger for samples deformed at \( \varepsilon = 6500 \ \text{s}^{-1} \) mainly because of the higher strain rate to which they were submitted.

Moreover, all the specimens except \( \text{H/D} = 0.44; \ \varepsilon = 3250 \ \text{s}^{-1} \) showed an oscillatory behavior after \( \sigma_y \). The cyclic softening and hardening observed for \( \text{H/D}=0.11 \) group has no physical explanation. Nevertheless, in Figure 3, we can...
associate the unusual behavior to the presence of high frequency oscillations in the transmitted pulses. As shown in Eq (E), the average stress is strongly dependent on the transmitted pulse. If the $\varepsilon_T$ signal is unstable, it will generate a less accurate dynamic stress-strain curve.

![Stress vs strain plots](image)

**Figure 8 - Stress vs strain plots.**

4 CONCLUSIONS

Sample dimension and strain rates were used to understand how the test set-up influences the stress equilibrium and the strain rate behavior during the impact, in the split Hopkinson Pressure Bar experiment. Concerning the achievement of stress equilibrium during the impact, it is possible to state that not only H/D ratio has considerable influence on the stress equilibrium during the experiment but also the strain rate, suggesting that for any H/D ratio there is a $E_{\text{incident}}$ threshold. Concerning the strain rate constancy during the impact, all the groups, but the 0.11 ratio, achieved a plateau with constant strain rate. It is possible to see that the strain rate decreases during deformation of H/D = 0.11 samples. The plot of the dynamical stress-strain curves of UHMWPE samples exhibit strain-hardening after the compressive yield strength, regardless the experiment set-up. The oscillatory behavior post-yield strength, especially of the H/D=0.11 group, was associated to the bad quality of the obtained transmitted signal. Results suggest that the dynamic mechanical properties are mainly controlled by $\dot{\varepsilon}$ and $E_{\text{incident}}$, rather than by the specimen H/D.
5 REFERENCES