The Compressive Response of Boron Carbide Ceramic under High Strain Rate

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Abstract

The boron carbide (B4C) ceramic is suitable material for armour application due to its low density, high hardness and compressive strength. It is subjected to high strain rate of loading during the projectile impact. Therefore, in this study, the compressive response of B4C is determined under low and high strain rate of loading using Modified Split Hopkinson Pressure Bar (MSHPB) test. The experimental results indicated that the uniaxial compressive strength of B4C ceramic is not sensitive to the strain rate of up to 103 s-1 and the failure of the B4C specimen was sudden and catastrophic under the uniaxial compressive loading at both low and high strain rate.

1 Introduction

Ceramics are suitable candidate for the armour design due to it is superior properties like high hardness and high strength to weight ratio. Boron carbide (B4C) ceramic is widely used for the armour design due to its higher hardness, compressive strength and low density among the advance ceramic materials [1].

The projectile impact on the ceramic layer develops strain rate in the range of $10^3 - 10^4\ s^{-1}$ [2]. Therefore, it is essential to understand the B4C ceramic response at these strain rates and also the effect of strain rate on its behaviour. The most of the available studies of B4C ceramic for armour application was focused on the strength of the material under shock loading where the material experiences strain rate of above $10^5\ s^{-1}$ [3]–[6]. There is very few studies are available on B4C response at the strain rate range of $10^{-3} - 10^4\ s^{-1}$.

Paliwal and Ramesh [2] conducted uniaxial compressive tests at strain rate range of $10^{-6} - 2\ \times 10^2\ s^{-1}$ to study the dynamic failure and strength of the B4C ceramic using modified split Hopkinson pressure bar test and high speed camera. Hogan et al. [7] studied the effect of processing-induced defects on the dynamic compressive strength and failure of B4C using SHPB. The material was investigate at strain rate range of $3.5\times 10^2 - 10^3\ s^{-1}$. There is no other studies are available in these strain rate as per the author knowledge. Therefore, in this study the response of B4C ceramic was explored under high strain rate of loading. The Split Hopkinson pressure bar setup for the metal testing is modified for ceramic testing in the current study.

2 Experimental Procedure

The commercially available hot pressed boron carbide ceramic tile was used for the current study. The B4C specimens for the quasi-static, SHPB and density measurements were machined from the 100 mm × 100 mm × 5 mm and 10 mm thick tiles using the Wire-cut Electrical Discharge Machine (WEDM). The WEDM machining quality is mainly depends on the electrical conductivity and ductile or brittle nature of the material. Though the B4C ceramic has sufficient electrical conductivity to be machined using WEDM, due to its brittle nature, the machining was very difficult and time consuming process. The quality of the surface finish after machining the specimen by WEDM was extremely good due to the slow rate of machining and intense care. Density of the B4C was measured using Archimedes method as per the guidance of ASTM - C373-16 and the measured density was 2.50 g/cc.

Cylindrical B4C specimens of 5 mm diameter and 5 mm length were used for uniaxial compressive experiments at quasi-static and high strain rate loading see Fig. 1. The loading surface of the specimens were polished to 6 Bxm using the Buehler diamond impregnated metal discs of 45 Bxm to 6 Bxm to eliminate the premature failure due to the presence of surface defect. The surface of the specimens were examined by optical microscope before the testing to ensure the surface is defect free. Specimens with unpolished surface was also tested under the quasi-static and high strain rate loading. The end friction between the loading platens of the testing machine and the specimen surface builds the complex stress and the testing is no more uniaxial. Therefore, lubricant was applied on the specimen surface to minimize the interface friction during the testing.

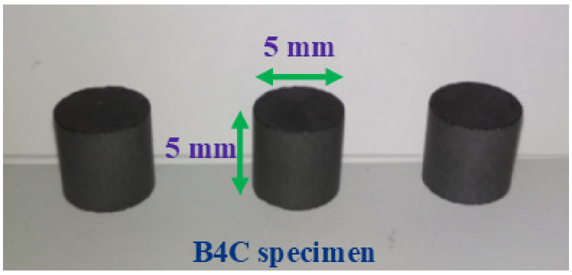

Figure 1: WEDM machined B4C specimens

The quasi-static test was carried out using the INSTRON Universal Testing Machine (UTM). The UTM loading platen hardness was lower than the hardness of B4C ceramic. The harder B4C indent into the loading platen due the large difference of hardness. Therefore, harder material of tungsten carbide (WC) platens of the diameter 13 mm, 30 mm, 50 mm with 10 mm thick was placed between the loading platen and B4C ceramic specimen. The quasi-static tests were conducted with strain rate of $10^{-3}\ s^{-1}$ and $10^{-2}\ s^{-1}$.

Modified split-Hopkinson pressure bar (MSHPB) apparatus was used to measure the uniaxial compressive strength of B4C ceramic under high strain rate. The SHPB apparatus for metal testing is modified for the ceramic testing. The apparatus contains striker of various length, incident, transmission and momentum trapper

Table 13: Detail of pulse shaper and insert

	Material	Dimension
Pulse shaper	Copper	5 mm diameter and 0.5 mm thick and 8 mm diameter 0.5 mm thick
Insert	Tungsten carbide	13.1 mm diameter and 6 mm length
Insert confinement	Steel	Inner diameter = 13.1 mm, Outer diameter = 20 mm,Length = 5.9 mm

bar of 2000 mm. the bar material is vascomax steel with density of 8080 kg/m^3, elastic modulus of 196.4 GPa and poisson's ratio of 0.3. The same has been modified by introducing thin copper pulse shaper between striker and the incident bar and steel confined WC inserts in the interface of incident bar-specimen and specimen-transmission bar see Fig. 2. The detail of the insert and pulse shaper is given in Table 1.
The WC inserts is protect the incident and transmission bars from the indentation of B4C specimen due to the high hardness. The WC inserts was confined by the steel rings to prevent the inserts failure beforehand the ceramic undergoes failure. The function of copper pulse shaper is to increase the rise time of the incident pulse which helps to maintain the stress equilibrium in the ceramic specimen throughout the test. Several SHPB trials with different impact velocity and striker length were conducted on copper pulse shaper to establish the required shape of the incident pulse. The dimension of the pulse shaper is finalised based on the trial test results. For further details regarding the design and modification of the SHPB for the ceramic testing can be seen in [8].

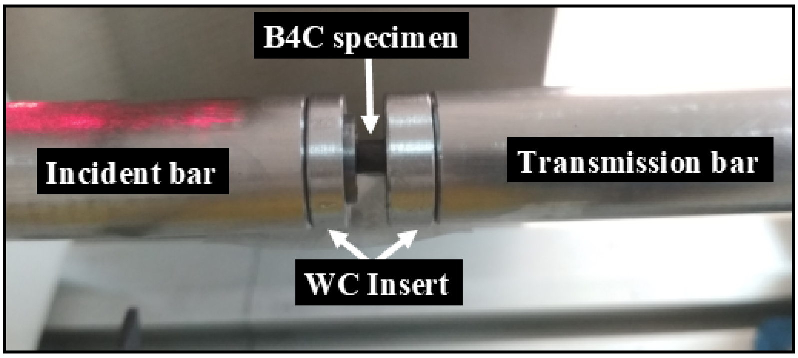

Figure 2: Modified split Hopkinson pressure bar setup for testing the ceramic material

3 Results and discussion

3.1 Quasi-static test

The B4C ceramic stress-strain relationship at the strain rate of 10^{-3} s^{-1} is shown in the Fig. 3. The average uniaxial compressive strength of the B4C ceramic was

3600 MPa. Ceramic specimen fracturing and spalling was observed during the end of test. The B4C specimen failed catastrophically after the specimen attains the capacity and the most of the ceramic specimen became powder. It was difficult to collect all the failed material due to fineness of the crushed ceramic. Therefore, the crushed B4C specimen of little quantity is collected and it will be analysed further for understand the fracture and failure mechanism of B4C ceramic under quasi-static loading.

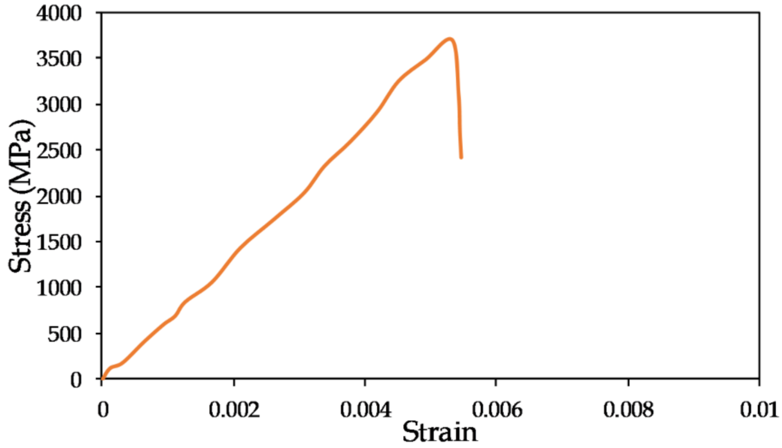

Figure 3: Stress-strain relationship of B4C at strain rate of $10^{-3}\ s^{-1}$

3.2 High strain rate loading

The SHPB strain signal of the current experiment for 200 mm striker is shown in the Fig. 4. The rise time the signal is increased by copper pulse shaper. The impedance match of the inserts and the SHPB bars were ensured by trial experiments without any specimen and it is observed that the incident strain signal completely passed through the inserts.

Hence, the dimension and arrangement of the inserts is satisfactory for the SHPB experiment. The B4C specimens then tested under various strain rate. Maximum strain rate achieved in the current experiment was $10^3\ s^{-1}$. For the higher strain rate the striker velocity increased, however the signals measured in the transmission bar was not appropriate and was difficult to establish the stress-strain relationship and calculate the strength of B4C ceramic, therefore these tests results were excluded. In future, the B4C ceramic response at the strain rate above $10^3 s^{-1}$ will be studied in by fixing the strain gauges on the surface of the specimen. The strain rate sensitivity of the B4C ceramic is studied by comparing the strength at various strain rate. It is observed from the experimental results that the strength of the B4C ceramic is not sensitivity in the strain rate range of 10^{-3} to $10^3\ s^{-1}$(Fig. 5) and the similar behaviour was reported by [2, 7].

Therefore, it can be concluded that the B4C ceramic is strain rate independent for the strain rate up to $10^3\ s^{-1}$. The failure of the B4C was axially splitting and the failure was exactly at the center of the specimen for the strain rate of $3 \times 10^2\ s^{-1}$ and the failure surface of the B4C was rough which indicates the excellent shear

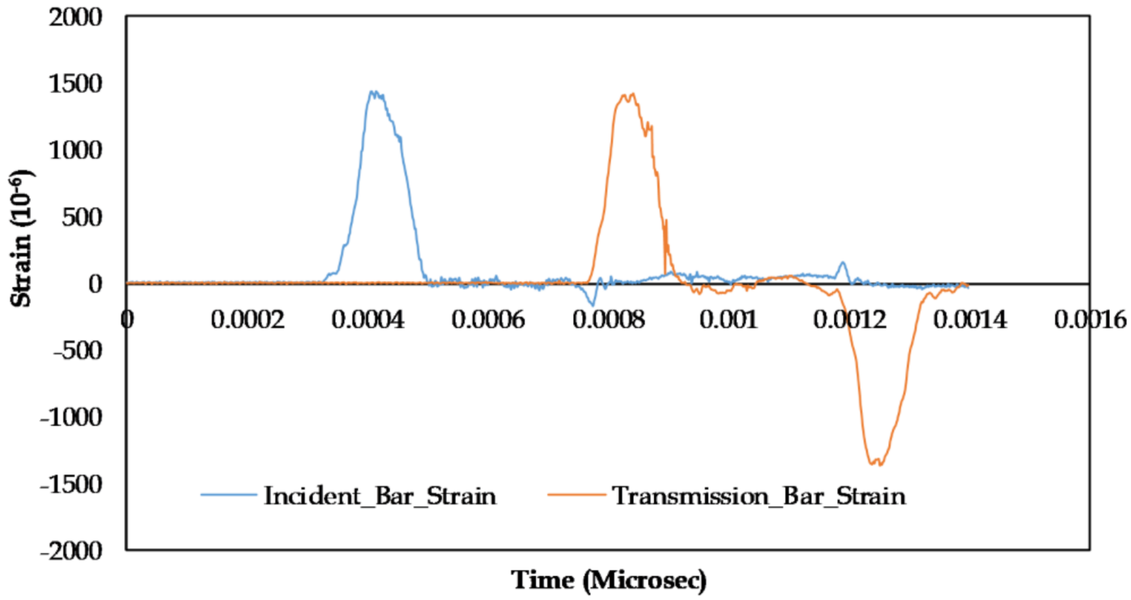

Figure 4: Strain signal of SHPB without specimen and with the 13 mm diameter insert (striker length and impact velocity is 200 mm and 13 m/s respectively)

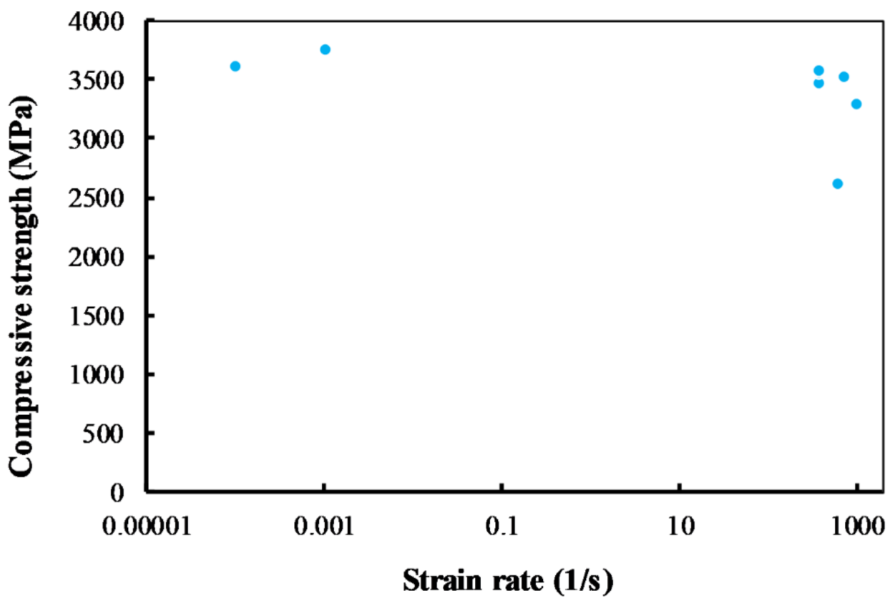

Figure 5: . Uniaxial compressive strength of B4C at various strain rate

resistance of the material. At higher strain rate the specimen becomes powder and the fractured fragments were similar to the quasi-static loading. The failed ceramic was collected for the further analysis of the fragment shape and size and the fractured surface of the B4C for the future study.

4 Conclusion

The uniaxial compressive strength of the B4C ceramic is determined at the quasi-static and dynamic loading condition and the strain rate ranged from $10^{-3}s-1$ to 10^3 s^{-1}. The specimens were machined by wire-cut EDM and tested under dynamic loading using split Hopkinson pressure bar setup. The experimental results showed that the uniaxial compressive strength of B4C is not sensitive to the strain rate as the strength was almost same in all the strain rate loading. The failure of the ceramic under both quasi-static and dynamic loading condition was catastrophic and crushed to powder. The failed B4C ceramic is collected and its failure surface and fragments will be analysed for the understanding the fracture and failure of this material under various loading condition.

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