Computational investigation of the dynamic response of silicon carbide ceramic under impact loading

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Abstract

It is estimated that by 2027, the global ballistic ceramic composites market would reach a value of US $3.67 billion. Many nations are increasing their military spending in order to better safeguard their military personnel, which has resulted in a tremendous increase in the market. As a result of the growing need for lighter, stronger, and harder ballistics, SiC-based composites are predicted to be the most lucrative of all ceramic materials. The study describes a finite-element model for ceramic carbide based on Johnson and Holmquist’s well-suited constitutive model for ceramics. The dynamic material tests of Strassburger et al. [Strassburger, E., H. Senf, and H. Rothenhäusler, 1994 Fracture propagation during impact in three types of ceramics. Le Journal de Physique IV. 4: C8-653–C8-658.] were replicated computationally to develop further insight about the material behavior under impact loading. Materials were simulated using the elastic properties and Johnson-Holmquist (JH-2) material models, respectively, for metal and ceramic materials. The stress distribution, damage progression, and failure of the material were accurately predicted by the results. The damage pattern, failure type, and method of failure are all examined as a result of altering projectile velocity. Computational data is utilized to verify the model’s accuracy and offer insight into the ceramic’s reaction to high strain.

1. Introduction

There has been a surge in the use of ceramics for armor applications during the past several decades. They are excellent for light armor systems because of their low density and strong compressive strength [1–3]. To establish ballistic performance of different ceramics used in armor system various testing methods have been developed [4–6], but in most of the testing methods, depth of penetration and projectile residual velocity is determined after impact and does not reveal the damage mechanism during the projectile penetration [7]. The numerical simulation have proven to be the best way to understand the progressive internal damage behavior which otherwise could not be captured easily experimentally [8]. To model ceramic behavior under impact loading condition two main points shall be considered. First, the damage initiation and evolution, which appears just after impact and, second the penetration of projectile lasts for few microseconds after impact [9].

Various constitutive models have been proposed by different authors to illustrate the dynamic response of ceramic under impact-loading using continuum damage mechanics approach. An exponential law was used for statistical distribution of planer and circular-fractures in ceramics by Curran et al [10]. A maximum principle tensile stress proposed by Wilkin [11] and enhanced by Walker et al [12], a pressure-criterion suggested by Taylor et al [13] to and an equivalent stress by Rajendran and Grove [14, 15] derived from the Griffith criterion are also proposed, where micro crack propagation caused by compressive and tensile stress was incorporated in finite element and meshless method for describing the response of ceramic under impact loading [16].
continuum damage model using stress-based damage evolution law and critical level of damage based failure criterion was proposed by Fahrenthold [17] for calculating depth of penetration in a target by an impactor.

To model the constitutive behavior of alumina a phenomenological approach was used by Simha et al [18]. The compressive strengths were determined by defining progressive fragmentation as scalar damage variable. The model was used to predict the penetration depth in the target materials by utilizing element removal scheme and Mie Gruneisen equation of state. Similarly, a rate depended, continuum damage model was proposed by Zuo et al [19] for finding dynamics response of alumina.

On the other hand, many other authors investigated discrete nature of cracks in ceramics besides continuum damage approach. A nucleation and propagation of discrete cracks in the arbitrary path by utilizing cohesive fracture model was presented by Camacho and Ortiz [20]. They used a constitutive model by adopting Mie Gruneisen equation of state combined with power hardening law. In the same way, to study the mechanical behavior of micro cracks a linear, homogeneous, and isotropic model was presented by Zhou and Molinari to investigate the probabilistic failures in ceramics [21, 22]. They used the interface between elements as possible cracks using cohesive elements. Followed by, Lee et al [23] presented a discrete damage model by utilizing a cohesive fracture law with node separate algorithm for tensile and Mohr-Coulomb law for compressive failures respectively. More crack propagation was observed by implementing tetrahedral elements instead of hexameral. In the identical way numerical and experimental study of sandwich structure for crack propagation under impact loading was carried out by Wang et al [24]. In the numerical simulation discontinuous Galerkin peridynamic method was employed to capture the cracks produced. The result reveals that the numerical model reproduced the same radial and circumferential cracks produced by the experimental result. Furthermore, Wu et al [25] utilized the peridynamic method to simulate the fracture mechanism in glass under low velocity impact loading. The materials dynamic response of non-porous silicon carbide under dynamic load was carried out by researchers [26]. The result reported the dependency of void collapse mechanism on the impact velocity. Another study of numerical simulation validated by experimental results were conducted by Cheng et al [27]. The close agreement between experimental and numerical results by reporting compressive strength and crack types.

To investigate the post impact behavior of brittle materials, Johnson and Holmquist are known as the JH-1 [28] and JH-2 [29] materials model are widely used. Both models explained compressive and tensile strength and failure performance of the brittle materials. For the two, Johnson–Holmquist (JH-2) was shown to be the best model for describing the dynamic response of ceramics under ballistic stress, with excellent findings [27, 30].

It should be noticed that any constitutive equation and embody assumptions, some of which are bound to the extent of the model. For example, the failure initiation in ceramic materials is, largely linked to the presence of microscopic defects [31]. Thus, a modeled constitutive equation must embody this effect to some extent. This can be achieved by the correct balance between precise interpretations of the physical phenomenon while sustaining some degree of computational efficiency. The JH-2 can represent the crack initiation and propagation via a damage variable and has been applied widely in numerical-simulations by many researchers [27, 32–36] for prediction of damage in ceramics under impact loading conditions. The JH-2 approach has been employed in Ansys-Autodyn as new alternative of the general ‘Johnson Holmquist’ model.

Although the JH-II material model is used by many researchers for dynamic study of ceramics but from the literature, it is revealed that the existing numerical modeling and experimental study does not provide the detail insight about crack propagation, damage phenomenology, fracture behavior, dynamic strength of SiC [8]. These properties are very important to be explored for the design of ceramics armor system. The numerical simulation using JH-II material model imbedded in Ansys- Autodyn is helpful for understanding the internal damage mechanism and failure modes, and damage velocity tracking which cannot be captured using experimental setup.

In this paper the detailed three-dimensional finite element simulations crack initiation and propagation in Silicon Carbide material under impact loading condition is studied. For the validation of numerical results the experimental phenomena of Strassburger [7] is used. The couple boundary conditions are implemented as interaction between steel impactor and silicon Carbide (SiC) target plate. For post ballistic behavior of the target plate JH-2 material model is used to visualize the damage and failure modes. Specially, the damage phenomenology and crack propagation velocities for different type of fractures modes is analyzed. A brief description of numerical setup is given in the section 2. After that, the FEM model’s specifics, such as material properties, loading inputs, boundary conditions, and material model parameters, are discussed in depth. This section compares the findings of the simulation with the experimental data, dynamic crack propagation processes. The conclusions and discussions are also drawn.
2. Simulation set-up and constitutive laws

2.1. Meshing and simulation setup

Finite element based numerical model was developed to investigate the penetration, damage, and failure mechanisms of the target material after projectile impact. The finite element modeling was carried out in the commercially available finite element code Ansys Autodyn. The dimensions and material properties of the target plate were the same, as were used during the experimentation [7]. For verification of the numerical simulation the edge-on-impact (EOI) test method developed by Strassburger et al [7] is used. The detail of the experimental setup is given in figure 1.

A rectangular SiC plate of dimensions 100 mm \( \times \) 100 mm \( \times \) 10 mm is targeted by a cylindrical projectile of diameter 30 mm and length 23 mm as per the experimental requirements. Solid model of EOI setup is shown in figure 2. To reduce computational cost a panner symmetry condition along \( X = 0 \) and \( Y = 0 \) plane is used to create a quarter model of the setup figure 3.

The 8-noded hexagonal element 3D mesh was used [37] for finite element model of the projectile and target plate as shown in the quarter plate of the figure 4. The target plate was divided into different mesh regions with mesh coursing in radial direction from inner to outer region in order to optimize the accuracy, stability and efficiency of the process. The mesh size varied between 0.2 to 1.4 mm which leads to total 500,890 elements. It
was observed that mesh size 0.4 mm gave the result in close agreement to the experimental values. Upon multiple variation in mesh sizes from 0.2 to 1 mm the convergence was observed at element size of 0.4 mm. This mesh transition among the regions was sufficient for prevention the reflected stress waves from the target material boundaries and erosion model (geometric strain = 1.2) was defined to incorporate the removal of distorted elements during simulations. For modelling of contact between bullet and target eroding_surface_to_surface, by means of the automatic_nodes_to_surface routine were used [38]. This type of contact allows the contact to erode when element erodes and work perfectly as the layers of the parts erode during penetration. The fixed boundary conditions (BCs) were applied to the upper and lower sides of the target plate as per the experimental setup shown in the figure 4.

2.2. Constitutive law: projectile

The Johnson-Cook (JC) [39] constitutive equation is commonly used material and damage model for ductile materials in ballistic applications. In fact, it is the most frequently used empirical model in ballistic science and engineering. It is a viscoelastic model and has been developed based on the experimental data at various strain rates and temperatures. The JC model is given by equation (1).

\[
\sigma_Y = (A + Be^C)(1 + C \ln \varepsilon^d)(1 - T^m)
\]

Where \(\sigma_Y\) is the dynamic yield strength and \(A, B, C, n, m\) are material constants while \(T^*\) is the homologous temperature when determining these constants. In addition to the material behavior model, an equation of state (EOS) is necessary to define the link among the local density, the hydrostatic pressure, and local specific energy.
In the present numerical modeling, Gruneisen EOS was used as given by equation (2) \[ P = \frac{\rho_0 C_{sp}^2}{\mu} \left[ 1 + \left( 1 - \frac{\gamma_0}{2} \right) \mu - \frac{\gamma_0}{2 \mu} \right] + (\Gamma_0 + a \mu) E_{int} \] (2)

Here P represents pressure, \( C_{sp} \) is the intercept of vs–vp curve and \( \Gamma_0 \) is a Gruneisen coefficient. The term \( \mu \) can be defined as \( \mu = \frac{E}{\rho C} - 1 \). In addition to the EOS and constitutive law, damage model is also needed to accumulate the damage as a function of increasing load. Accordingly, Johnson–Cook damage model based on the accumulative plastic strain and failure was employed when the damage parameter exceeded the value of 1.

The damage parameter \( D \) is a scalar quantity in this case and is computed with the equation (3) \[ D = \sum \frac{\Delta e^p}{e_f^p} \] (3)

Where, \( \Delta e^p \) is the plastic equivalent strain (scalar quantity), and \( e_f^p \) is the ultimate plastic strain expressed as in equation (4).

\[ e_f^p = [D_1 + D_2 \exp(D_3 \sigma^s)] \left[ 1 + D_4 \ln \left( \frac{e_{pl}}{e_0^p} \right) \right] \left[ 1 + D_5 \left( \frac{T - T_r}{T_m - T_r} \right)^m \right] \] (4)

Equation (4) designates the material crack locus in term of stress triaxiality denoted by \( \sigma^s \) that is specified by the ratio of hydrostatic pressure to Von-Mises stress. Similar to strength model, damage model in Johnson-Cook formulation also separates temperature and strain effect in different parts incorporating damage coefficients such as \( D_1, D_2, D_3, D_4 \), and \( D_5 \). The Johnson–Cook material model constant parameters of metallic 4340 steel used in the simulation were collected from \[ 28 \] and are given in table 1. To represent the pressure-volume relationships, along with material model (J–C material model) an equation of state (Mie-Gruneisen) must be used for higher impact velocity.

2.3. Constitutive law: Ceramic target material

For the correct prediction of the ceramic front plate behavior, Johnson–Holmquist-II \[ 41 \] model was used to reproduce the brittle behavior of the ceramic material. To correlate the pressure with the volumetric change and compressibility modulus a polynomial equation of state was used. The material stress (\( \sigma^s \)) at high-pressure and strain-rates can be easily defined by varying fracture strength (\( \sigma^f \)), intact strength (\( \sigma^i \)), and damage parameter (D) with the help of equation (5) \[ \sigma^s = \sigma^i - D(\sigma^i - \sigma^f) \] (5)

The normalized intact stress (\( \sigma^i \)) and fractures stress (\( \sigma^f \)) is defined in equations (6) and (7), respectively.

\[ \sigma^i = A(P^s + T^s)^B(1 + C \ln e^s) \] (6)
Where A, B, C, M, N are material constants and $P^*$ is the normalized pressure, $T^*$ is normalized hydrostatic tension, and $\varepsilon^*$ is dimensionless strain rate. The polynomial equation of state is given by equation (8) [43].

$$P_{HEL} = K_1\mu + K_2\mu^2 + K_3\mu^3$$  \hspace{1cm} (8)

Where the compressibility factor $\mu = \frac{\rho}{\rho_0} - 1$ with $\rho$ current density, $\rho_0$ reference density of material while $K_1, K_2, K_3$ are material constants. Similarly stresses at Hugoniot Elastic limit, HEL ($\sigma_{HEL}$) can be shown in equation (9).

$$\sigma_{HEL} = \frac{3}{2}(HEL - P_{HEL})$$  \hspace{1cm} (9)

Similar to the Johnson-Cook damage model, Johnson-Holmquist (JH-II) damage variable can also be expressed in terms of plastic strain expressed by equation (10).

$$D = \sum \frac{\Delta \varepsilon^P}{\varepsilon^P_t}$$  \hspace{1cm} (10)

Where, $\Delta \varepsilon^P$ = increment of plastic strain, $\varepsilon^P_t$ = plastic strain at fracture, it is a function of the actual pressure given by equation (11) [45].

$$\varepsilon^f = D_1(P^* + T^*)^{D_2}$$  \hspace{1cm} (11)

In all the above expressions A, B, C, M, N, T, HEL, $D_1$ and $D_2$ are constants already available in the literature and are listed in table 2 [35].

In this research, Johnson-Holmquist model [41] described in earlier sections is used for Silicon Carbide material, which relate the pressure-volume to intact and fracture strength. The content values are taken from the literature [7, 35] for simulation purpose and are given in the table 2 below.

### 3. Results and discussion

The finite element simulations of EOI setup is carried out, where steel projectile is targeting SiC plate under different velocities from 100 m s$^{-1}$ to 1000 m s$^{-1}$. In EOI experimental setup Cranz-Schardin high-speed

### Table 2. Parameters used for Johnson-Holmquist model for SiC [7, 35].

| Parameter                          | Magnitude       |
|-----------------------------------|-----------------|
| Density, (kg cm$^{-3}$)           | $3.18 \times 10^{-3}$ |
| Young’s Modulus (E), (GPa)        | 427             |
| Compressive-Strength, (GPa)       | 3.41            |
| Bulk-Modulus, (GPa)               | 223             |
| Shear-Modulus, (GPa)              | 195             |
| Poisson’s Ratio                   | 0.140           |
| Strength-Data                     |                 |
| A                                 | 0.960           |
| B                                 | 0.350           |
| C                                 | 0               |
| M                                 | 1               |
| N                                 | 0.650           |
| Strain-Rate$_{Ref}$               | 1               |
| Tensile-strength, (MPa)           | 370             |
| Fracture-Strength, (MPa)          | 800             |
| HEL, (MPa)                        | 14567           |
| HEL-Pressure, (MPa)               | 5900            |
| HEL-Vol. Strain ($\mu$)           | 0.0242          |
| HEL-Strength, (GPa)               | 13              |
| Constants used for Damage         |                 |
| D1                                | 0.480           |
| D2                                | 0.480           |
| Equation of State Data            |                 |
| K1, (GPa)                         | 204.78          |
| K2, (GPa)                         | 0               |
| K3, (GPa)                         | 0               |
| $\beta$ (Beta)                    | 1               |

$$\sigma^*_t = B(P^*)^M(1 + C \ln \varepsilon^*)$$  \hspace{1cm} (7)
cameras are employed to monitor and capture crack pattern produced in SiC under ballistic loads. The schematic of typical failure types shown in figure 5 [7] is taken as reference to compare the simulation results. As can be seen, most of the cases the cone cracks are reported as first failure type, which initiates and propagates in radial dictation from impact side in the velocity direction. This is followed by short form of cracks (branches of fir-tree) at an angle to the main crack propagation direction as given in the figure 5 [7].

From numerical simulation results, the leading-edge based failure pattern is observed in between 5 to 21 μs after impact. The simulations results are compared with experimental findings as reported in literature and are summarized at different times after impact in figures 6 to 8 for the time 10 μs, 5 μs and 4 μs for velocities 150 m s⁻¹, 185 m s⁻¹ and 513 m s⁻¹, correspondingly. The result reviled that the primary cracks along with sharp edges are reported at the striking velocity of 150 m s⁻¹, which leads to crack type I and II just after propagation. These types of failures are very common in ceramics under impact loadings as reported by [7]. As the time reaches to 10 μs, the tree type secondary cracks zones are observed around the projectile edge. Furthermore, contours of shell shaped fragmentation and radial cracks is also noted as shown in figure 6. In the same way, in case of projectile velocity of 185 m s⁻¹ at 5 μs fuzzy cracks followed by radial and secondary cracks are observed in figure 7. Dense cracks are observed in the area ahead of projectile due to site nucleation. The crack density and damage intensify with increase in velocity as can be observed in figure 8. Denser field of fuzzy cracks propagation is reported in case of 513 m s⁻¹ projectile velocity compared to the previous two cases. Further cases of damage pattern under high impact velocities are presented in figures 9 to 11 for different simulation time at various velocities of 500 m s⁻¹, 800 m s⁻¹ and 1000 m s⁻¹ respectively. More damage and dense cracks are reported in case of higher velocity compared to case with lower

**Figure 5.** Fracture types in Ceramics under impact loading conditions [7].

**Figure 6.** Experimental (a) and Numerical (b) The pattern of damage at velocity 150 m s⁻¹ and at 10 μs.
velocity. This revealed that the crack density and propagation is directly proportional to projectile velocity. A decrease in field density with increasing simulation time was also reported. The similar results were reported by experimental study of the same cases.

In their experimental study, the fastest fracture velocity produced in ceramic, also called damage front velocity, was measured by Strassburger et al using high speed cameras. For finding this damage front velocity numerically image processing technique is used to measure distance of the fracture front tip, then the velocity is calculated based on time of crack propagation as shown in figure 12. The calculated damage front velocity compared to projectile striking velocity ranging from 100 m s\(^{-1}\) to 1000 m s\(^{-1}\). Upon calculation, the value of damage velocities measured for initial striking velocities of 150 m s\(^{-1}\), 185 m s\(^{-1}\), and 513 m s\(^{-1}\) are, respectively, 4000 m s\(^{-1}\), 5600 m s\(^{-1}\), and 9800 m s\(^{-1}\). These computed velocities are in close agreement with the experimental value presented by the reference shown in figure 12. Furthermore, an increase in damage velocity with an increase in projectile velocity is observed. As the damage velocity rise with increase of projectile velocity, such as for projectile velocity of 800 m s\(^{-1}\) the damage velocity of around 11600 m s\(^{-1}\) was reported, which is smaller by an amount of around 410 m s\(^{-1}\), than the damage velocity measured for initial velocity of 1000 m s\(^{-1}\). There is an agreement between experimental and numerical values in the range of 11% error. The assumption of a completely normal projectile impact on the target’s edge may be the cause of the reported inaccuracy, although in an experimental setting, it may be impossible to get a perfectly normal projectile impact. An experiment’s equipment may also go wrong, which can lead to a faulty result. Strassburger et al[7] experimental findings are found to be in close accord with the damage pattern and damage front velocity of ceramics through simulations.

In this way, the numerical model created in ANSYS AUTODYN is completely verified. The further use of the verified model for higher velocities revealed that the damage velocity, crack propagation and failure types can be captured for any kind of velocity impacts. Thus, the verified model can be used for computational study of

Figure 7. Experimental (a) and Numerical (b) the pattern of damage at velocity 185 m s\(^{-1}\) and at 5 µs.

Figure 8. Experimental (a) and Numerical (b) The pattern of damage at velocity 513 m s\(^{-1}\) and at 4 µs.
Figure 9. Damage patterns for striking at $V = 500 \text{ m s}^{-1}$ and $5\mu s$.

Figure 10. Damage patterns for striking at $V = 800 \text{ m s}^{-1}$ and $4\mu s$.

Figure 11. Damage patterns for striking at $V = 1000 \text{ m s}^{-1}$ and $6\mu s$. 
damage phenomenology, and the spreading velocities of different forms of fracture that are occurred in ceramic materials.

4. Conclusion

In this paper, three-dimensional finite element simulation of Silicon Carbide material was successfully completed in ANSYS-AUTODYN. The experimental data used from literature was analyzed using Johnson and Holmquist (JH-II) material model, to visualize the damage processes during impact. The damage phenomenology and damage propagation velocity are recorded at different projectile velocities. A close resemblance between numerical and experimental data was observed. Furthermore, it was revealed that, the damage pattern and damage velocity both increased with increase of projectile striking velocities. This study suggest that numerical simulation can be used for capturing damage phenomenology, crack propagation velocity and failure modes in any kind of ceramics under dynamic loading condition without using expensive experimentations.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

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Figure 12. Damage velocity versus Projectile initial velocity.
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