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by C. G. Fountzoulas, B. A. Cheeseman, and J. C. LaSalvia

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14. ABSTRACT

The present investigation is a continuation of our previous study [1] on the ability of the phenomenological Johnson-Holmquist model to predict the observed damage induced by spheres of tungsten carbide (WC) striking confined cylinders of silicon carbide (SiC) at velocities between 63 m/s to 500 m/s. In this study, the WC was modeled using the Johnson-Cook plasticity model along with a principal stress failure criterion calibrated with recently available experimental data [2,3]. Johnson-Holmquist model parameters along with modifications incorporated to brittle damage models included in AUTODYN – tensile crack softening and stochastic failure - were varied to study their influence on the simulated crack patterns. Comparisons with the cracking from the simulations and the experimentally observed damage are described and ongoing efforts to improve the numerical results are discussed.

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SIMULATION OF BALLISTIC IMPACT OF A TUNGSTEN CARBIDE SPHERE ON A CONFINED SILICON CARBIDE TARGET

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The present investigation is a continuation of our previous study [1] on the ability of the phenomenological Johnson-Holmquist model to predict the observed damage induced by spheres of tungsten carbide (WC) striking confined cylinders of silicon carbide (SiC) at velocities between 63 m/s to 500 m/s. In this study, the WC was modeled using the Johnson-Cook plasticity model along with a principal stress failure criterion calibrated with recently available experimental data [2,3]. Johnson-Holmquist model parameters along with modifications incorporated to brittle damage models included in AUTODYN – tensile crack softening and stochastic failure - were varied to study their influence on the simulated crack patterns. Comparisons with the cracking from the simulations and the experimentally observed damage are described and ongoing efforts to improve the numerical results are discussed.

INTRODUCTION

Ceramics are materials that possess characteristics such as low density, high hardness and high compressive strength that make them ideal for use in light armor; however, ceramics are also brittle and have a low tensile strength, which complicates the design of such systems. Numerous experimental investigations have been performed since the 1960s to develop an understanding of the behavior of ceramics under high velocity impact, the phenomenology of ceramic failure, and the behavior of the failed ceramic under large pressures. These studies have been crucial in the understanding their performance and also in development of ceramic material models.

As the failure phenomenology of the ceramic became known, numerous material models were developed in an attempt to accurately depict the behavior of the ceramic under high rate loadings. Perhaps the most widely utilized and well known of the material models developed for ceramics are the ones developed by Johnson and Holmquist [4,5], which have become known as JH-1 and JH-2. Johnson, Holmquist and Beissel have also extended the ceramic model to account for phase transformation and this version is known as the JHB model [6]. The JH-1 and JHB models have been used to successfully model the range of possible ceramic-penetrator interactions -

interface defeat, dwell-penetration transition and direct penetration - and provide a great deal of insight into these interactions. While a number of the model constants are determined from dynamic characterization experiments, such as plate impact, a few of the constants and failure behavior have to be inferred from penetration experiments. It is this inferred behavior, such as how the ceramic transitions from the intact strength to its failed strength and the actual strength of the comminuted material, which, in part, are of interest in the current investigation.

In addition, these aforementioned ceramic material models have been developed for high velocity impact-penetration calculations of ceramics. This work investigates the ability of the phenomenological Johnson-Holmquist ceramic material models to predict the observed damage, such as the ring, conoid and radial cracking, introduced in confined cylinders of SiC struck by WC spheres at low to intermediate (63 m/s - 500 m/s) velocities. The effect of specific strength and failure model parameters as well as the inclusion of stochastic strength and tensile crack softening on the damage development are described; in addition, the contribution and sensitivity of the these parameters on the accuracy of the solution when compared to the experimentally determined damage patterns are discussed.

EXPERIMENTAL DETAILS

Details of the impact experiments have been reported by LaSalvia et al [7]. Armor-grade SiC-N manufactured by Cercom, Inc.†, was machined into cylinders 25.4 mm in diameter and 25.4 mm in length (nominal) and slip-fit (0.025 mm nominal diameter difference) into Ti-6Al-4V cups. The cylinders were then center impacted with 6.35 mm diameter WC‡ spheres from Machining Technologies, Inc., at velocities ranging from 50 – 500 m/s. Figure 1 shows the sectioned cylinders and the corresponding cracking induced in them from the impact of the WC spheres.

NUMERICAL SIMULATIONS

Four experiments that spanned the breadth of the impact velocities, 63 m/s, 161 m/s, 322 m/s and 500 m/s, were chosen to be simulated using the nonlinear analysis software AUTODYN. Using the geometry detailed above, the projectile and the SiC target were discretized using Smooth Particle Hydrodynamic (SPH) with a particle size of 0.5 mm while the Ti-6Al-4V sleeve was meshed using the solid elements. The Ti-

† BAE Advanced Ceramics Division

‡ 6 weight percent cobalt

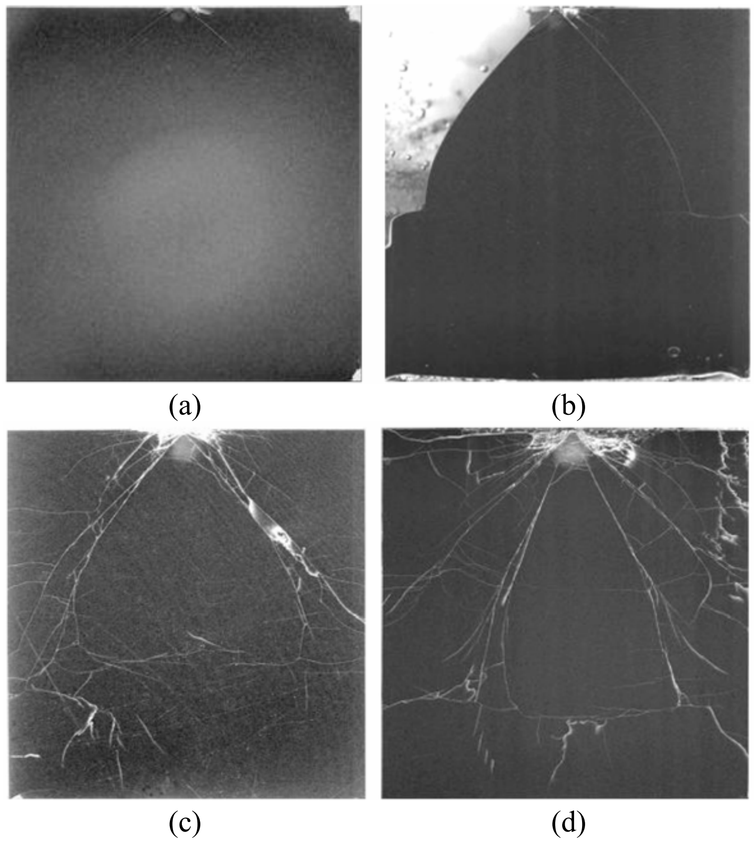


Figure 1. Cross section of silicon carbide cylinder after being impacted by a tungsten carbide sphere at (a) 63 m/s, (b) 161 m/s, (c) 322 m/s, and (d) 500 m/s.

6Al-4V sleeve was modeled using a shock equation of state (EOS) and a Steinberg-Guinan strength model with parameters from the AUTODYN material library. The SiC strength and failure were modeled using the JH-2 ceramic model with the values reported in [6] recast for the JH-2 model. As mentioned above, how the ceramic transitions from its intact to failed strength is of interest. In the JH-1 and JHB models, the transition is instantaneous once a critical damage value is attained. However, in the JH-2 model, the degradation of strength is incremental: the strength degrades as damage develops. The present paper details the results using the JH-2 model; however ongoing efforts are also investigating the instantaneous degradation utilizing the JH-1 model and will be reported in the future. The WC was modeled using the Johnson-Cook plasticity model with constants reported in [8] and a principal stress tensile failure model with constants reported in [2,3]. The influence of the failed strength of SiC was studied by varying the coefficient B and exponent M constants in the equation for the normalized failed strength σ^*_f [4]:

$$\sigma^*_f = B(P^*)^M(1 + C \cdot \ln\dot{\varepsilon}^*) \quad (1)$$

where variables P*, C, and $\dot{\varepsilon}^*$ are the normalized pressure, strain-rate coefficient, and normalized strain rate, respectively. The normalized pressure is defined as $P^* = P/P_{HEL}$ where P_{HEL} is the pressure at the Hugoniot Elastic Limit (HEL). For the JH-2 model, the strength of the material is described by a smoothly varying function of the intact strength, failed strength, and damage. The normalized strength is given by:

$$\sigma^* = \sigma^*_i - D(\sigma^*_i - \sigma^*_f) \quad (2)$$

where σ^*_i, σ^*_f and D are the normalized intact strength, normalized fracture strength and D is the damage ($0 \leq D \leq 1$). The normalized equivalent strengths, σ^*, σ^*_i, and σ^*_f, have the form $\sigma^* = \sigma/\sigma_{HEL}$, where σ_{HEL} is the stress at the HEL.

With the JH models, damage is a function of the deviatoric strain of the material, which is representative of material in the high compression region ahead of an impacting projectile. In areas away from the impact region, the tensile and shear stresses may be of equivalent magnitude, which for brittle materials, may lead to tensile cracking. The ability of the JH models to model this tensile cracking is a function of maximum tensile hydrostatic pressure, T, which for the current effort was set to either 600 MPa or 750 MPa.

The simulation of the crack development in the SiC target was studied systematically using these values of hydrostatic tensile limit and varying the strength of the failed material by using two different sets of B and M constants, 0.2, 0.5, and 0.4, 1.0, respectively. Previous investigations have noted limitations with the JH models in the prediction of tensile cracks [9,10]. Clegg et al.[10] coupled a Rankine failure surface with the JH2 failure surface within AUTODYN thereby allowing tensile failure to be initiated by the maximum principal stress criteria. Post-failed response is defined by a crack-softening relation based on the fracture energy of the material. In addition, a Mott strength distribution [11] can be implemented in conjunction with the tensile crack softening algorithm and was also utilized in the current investigation. Each of the different tensile failure methodologies - hydrostatic tensile limit, maximum tensile principal stress, with and without crack softening, and with and without stochastic failure – was utilized for each of the impact velocities and is summarized in Table 1.

For most of our simulations, WC was modeled using the Johnson-Cook strength model and no failure criteria (i.e., the tungsten carbide could plastically deform but not fail), as in the previous work [1]. When tensile failure of WC was included, the

Table 1. Parameters used for the simulation of the crack development in the SiC target.

Normalized Fractured Strength (σ^*_f)				Tensile Failure Details				Impact Velocity (m/s)
				Hydrostatic Tensile Limit	Tensile Principal Stress (600 MPa)			
B	M	B	M			Crack Softening	Stochastic Failure	
0.2	0.5	0.4	1.0	●				63
0.2	0.5	0.4	1.0		●			63
0.2	0.5	0.4	1.0		●	●		63
0.2	0.5	0.4	1.0		●	●	●	63
0.2	0.5	0.4	1.0	●				161
0.2	0.5	0.4	1.0		●			161
0.2	0.5	0.4	1.0		●	●		161
0.2	0.5	0.4	1.0		●	●	●	161
0.2	0.5	0.4	1.0	●				322
0.2	0.5	0.4	1.0		●			322
0.2	0.5	0.4	1.0		●	●		322
0.2	0.5	0.4	1.0		●	●	●	322
0.2	0.5	0.4	1.0	●				500
0.2	0.5	0.4	1.0		●			500
0.2	0.5	0.4	1.0		●	●		500
0.2	0.5	0.4	1.0		●	●	●	500

maximum principal tensile stress criterion was utilized in conjunction with a tensile strength of 3.5 GPa [3].

Utilizing the hydrostatic tensile limit inherent in the JH-2 model, the conoid cracks readily observed in the sectioned ceramic cylinders were not reproduced when either set of M and B values and hydrostatic tensile limits, 750 MPa and 600 MPa, were utilized for simulations involving impact velocities from 63 m/s to 322 m/s. For the impact velocity of 500 m/s, the simulated conoid cracks resembled those observed experimentally at 161 m/s impact. The WC sphere, modeled without failure, rebounded for all the impact velocities.

When the JH-2 model was coupled with the principal tensile failure model, the simulations better approximated the experimental observations. More specifically, simulations utilizing a maximum principal tensile stress of 600 MPa more closely approximated the experimental observations when compared with those that used a value of 750 MPa, regardless of the values of the failed strength constants B and M. Although no quantitative conclusion can be drawn at this time regarding the utilization of the crack softening parameters or a stochastic strength distribution, it should be noted that when a stochastic distribution was utilized, the resulting cracking was appreciably different. Figures 2(a)-(d) show the crack patterns developed in the SiC for the cases

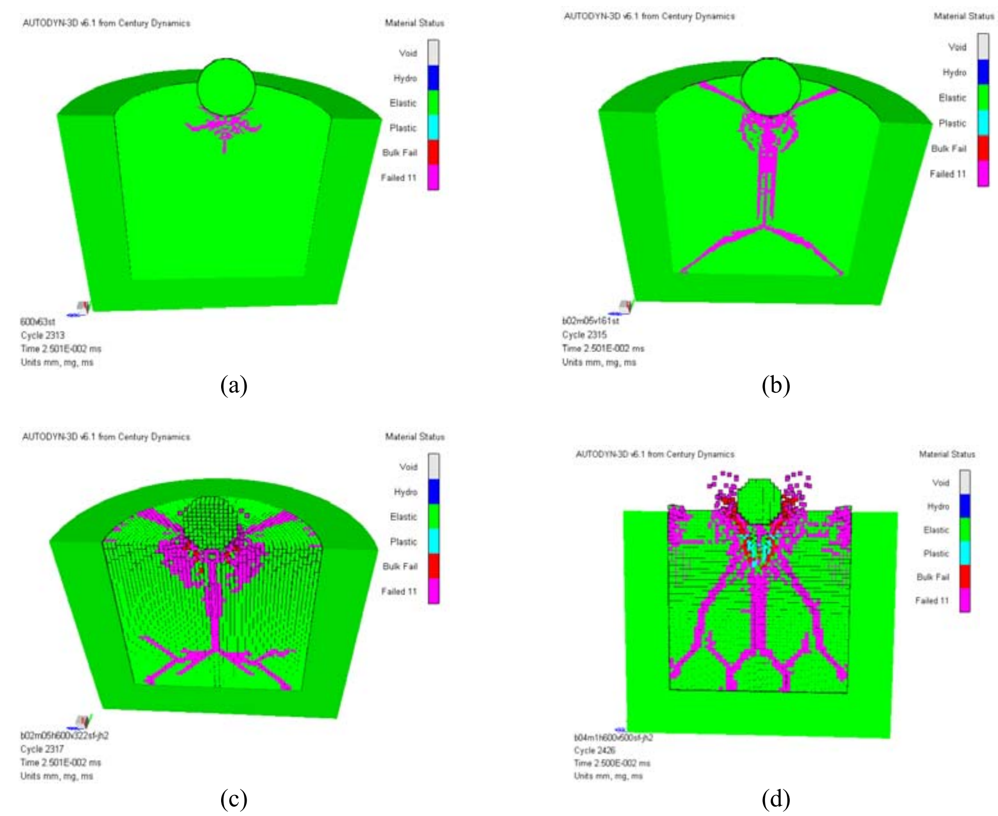
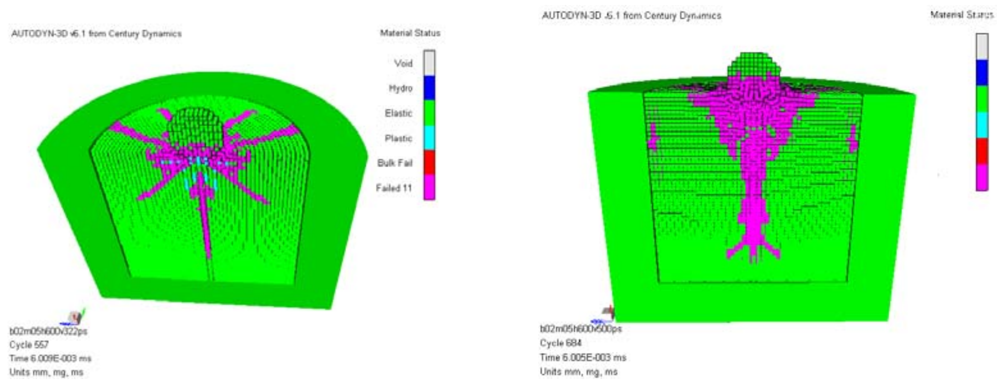


Figure 2. Simulation results for silicon carbide modeled using a JH2 model with a maximum tensile principal stress of 600 MPa with stochastic strength distribution and failed strength constants of B = 0.2 and M = 0.5 for impact velocities of (a) 63 m/s, (b) 161 m/s, (c) 322 m/s and (d) 500 m/s.

where the maximum principal tensile stress of 600 MPa and a plastically deforming, but not failing WC sphere, were used.

To study the effect of modeling the WC with a maximum principal tensile stress failure criterion, simulations were run with the SiC modeled with the JH-2 model with a maximum tensile principal stress of 600 MPa and two different failed strengths for impact velocities of 322 m/s and 500 m/s. For all cases, the WC sphere failed in the region of contact with the target. Shown in Figure 3(a), for the impact at 322 m/s with B = 0.2 and M = 0.5, the crack patterns most closely represented the cracking observed from the experiments. However, when the same parameters were utilized for an impact velocity of 500 m/s (Figure 3(b)), extensive damage was produced in the region of impact, which was not observed in the experiments. When B = 0.4 and B = 1.0 were utilized (Figure 4), conoid cracks were observed for both the 322 m/s and 500 m/s



322 m/s 500 m/s

Figure 3. Results at 6 µs for B = 0.2, M = 0.5. 600 MPa tensile strength for WC sphere.

322 m/s 500 m/s

Figure 4. Results at 4 µs for B = 0.4, M = 1.0. 600 MPa tensile strength for WC sphere.

impact velocities; however, qualitatively, crack patterns similarities with observations were not improved.

DISCUSSION

Although the extent of ceramic performance (dwell, dwell-penetration transition and direct penetration) while undergoing impact has been simulated [5,6], a number uncertainties exist when describing ceramic behavior. As discussed Holmquist and Johnson [6], the transition of the ceramic from its intact behavior to its damaged and comminuted response is not known. Additionally, at present, there is no accepted value of the strength of the confined comminuted material, as previous works utilize a wide range of values from 200 MPa [6], 1.3 GPa [5], and 4 GPa [12]. Moreover, improved modeling the tensile failure of the ceramic have been reported by coupling the compressive strength and damage modeling of the JH models with a Rankine failure surface [9,10] and recent investigations have cited the importance of incorporating the stochastic nature of ceramic strength [13]. The present ongoing investigation utilizes the results of sphere impact experiments at low to intermediate impact velocities to study these questions, along with the applicability of the JH models in these velocity regimes.

Not surprisingly, how the WC is modeled affects the resulting damage in the SiC. WC has been modeled without failure, which may be accurate for the lower velocity cases, and with a maximum principal tensile stress failure model, using recently obtained WC data [3] for the higher velocity cases. Qualitatively, the latter simulations resulted in relatively good agreement with the cracking observed in the SiC. However, more work is need and ongoing characterization of WC is being performed [3] to assist in improving the accuracy in simulating the WC failure. Until then, the current study on the applicability of the Johnson-Holmquist ceramic models to low to intermediate velocity impacts and further insights into the aforementioned questions will remain incomplete.

However, a few salient points can perhaps be drawn. In the experiments simulated in the current effort, tensile cracking of SiC is readily observed. The combination of the maximum principal tensile stress and properly selected B and M parameters of the failed stress of SiC resulted in a fair reproduction of the experimental data under the current circumstances. Investigations are ongoing in the utilization of crack softening utilizing the dynamic fracture initiation toughness measurements of SiC recently reported by Weerasooriya et al. [14] and stochastic strength to determine if these result in improved reproduction of the experimental observations.

CONCLUSIONS

The ability of the phenomenological Johnson-Holmquist ceramic model to predict the observed damage patterns induced by WC spheres striking confined cylinders of SiC at low to intermediate impact velocities was investigated. Simulations were also utilized to investigate the effect of the failed strength, tensile failure, and stochastic variability on the resulting damage induced in the ceramic. At present, no definitive conclusions can be drawn as the damage induced in the ceramic is influenced by behavior of the WC sphere, for which the modeling of failure has not been fully developed. Ongoing studies are being performed to further elucidate the effect of these properties.

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