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Research Article

Energy and Deformation during Explosive Compaction of ZrB_2-SiC Ultrahigh Temperature Ceramics

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To introduce a new technique and to choose the process parameters, ZrB_2-SiC ultrahigh temperature ceramics (UHTCs) were prepared by mixing and explosive compaction. The explosive kinds or explosive mass was variable so as to change the explosive impact energy. We have studied the relationships of the explosive impact energy, the tube deformation energy, the powder compaction energy and the ratio of the explosive mass to the tube mass (R), the relationships of the tube deformation energy, the tube equivalent strain and the mass ratio R, and the relationships of the densities of the ZrB_2 composites and the powder compact energy. The results show that the densities of the ZrB_2 composites reach 93.37% of theory density. For any kind of explosive, the reduction of the outer diameter and the equivalent strain of the steel tubes raises gradually with the rise of the mass ratio R. Generally speaking, the higher the explosion speed of the explosive is, the larger the deformation degree and the equivalent strain of the steel tubes are. The explosive impact energy can be divided into two parts: the tube deformation energy and the powder compact energy; with the rise of the mass ratio R, the tube deformation energy hardly changes, while the explosive impact energy and powder compact energy increase synchronously, and the densities of the ZrB_2 composites also increase gradually. The density of the ZrB_2 composites produced by different explosives orders from big to small as RDX, Ammonium Nitrate, TNT, and Urea Nitrate.

1. Introduction

Ultrahigh temperature ceramics (UHTCs) [1–3] are fragile composites which are composed of ZrB_2 or HfB_2, ZrC or HfC, and SiC. Essentially, these structural ceramics possess an excellent and unique set of bulk properties including unusually high melting points, high thermal conductivity, high elastic modulus, retained strength at high temperatures, relatively good thermal shock resistance, and modest thermal expansion [4].

Strategic interest in UHTCs has provided the aerospace industry with concrete opportunities to design a new generation of space vehicles with sharp leading edges (1 mm in radius) and smooth surfaces, resulting in much smaller, lighter and more efficient space vehicles than ever before. Moreover, such a new class of materials may overturn an age-old belief of aerodynamics that only a blunt-nosed as the vehicle repeatedly tears through the terrestrial atmosphere during hypersonic flights [5].

In 1930s, the American Air Force developed UHTCs initially. With many years' efforts of scientists and researchers, it has been shown that the UHTCs have good oxidation resistance by 1600°C and have been used in trial manufacture. There are two key techniques in preparing UHTCs: one is to control the process exactly, and the other is to introduce the advanced preparation process. Explosive compaction is a kind of process which produces high pressure and high temperature at the moment to compact the powder when the explosive is detonated [6]. The merits [7, 8] of this process are as follows: since explosion and sintering are completed in ultra short time (about several microseconds), not only the crystal grain does not grow up, but also the compound interface hardly diffuses or the diffusion degree is quite little (less than 100 nm). Thus, explosive compaction may be an optimal way to prepare new materials such as the bulk amorphous materials, the quasicrystal materials, and the nanocrystal materials.

Based on the research of the ZrB_2-SiC UHTCs prepared by mixing and hot pressing [9, 10], we adopted mixing

and explosive compaction to prepare the ZrB_2-SiC UHTCs, and we have studied the relationships of the explosive impact energy, the tube deformation energy, the powder compaction energy, and the ratio of the explosive mass to the tube mass (R), the relationships of the tube deformation energy, the tube equivalent strain and the mass ratio R, and the relationships of the densities of the ZrB_2 composites and the powder compact energy, in order to optimize the technological parameters during explosive compaction of the ZrB_2-SiC UHTCs.

2. Experimental Method

2.1. Process of Explosive Compaction. The set [11] as shown in Figure 1 is usually used in the direct method of the explosive compaction. The powder is packed into the close metal tube surrounded by a layer of homogeneous explosive. When the explosive is detonated, the powder is compressed by the steel tube which is compressed down by the convergent columnar impact wave from one side of the system. In this paper, the powders were put into a 20#-seamless steel tube, and the bottom of the tube was blocked by a steel plug. When being packed into the powder, the tube vibrated making the powder homogeneous and dense. Then, it was blocked by the other plug and set in the position of axis of the columnar paper tube. The wooden cone was set on the top of the steel tube to make the explosive produce the front edge of the compression. Homogeneous and dense explosive was put into the clearance between the steel tube and the paper tube. The explosive exploded vertically after the detonator was detonated.

The sizes of the steel tubes are as follows: the outer diameter is 18 mm, the wall thickness is 2 mm, the length is 100 mm, and the mass of each tube is about 18.9 g. The material of the upper plug and the lower plug is the 20# seamless steel bar, the sizes are both Φ14 mm $\times$ 10 mm, and the masses are both about 12.1 g. The size of the wooden cone is Φ18 mm $\times$ 15 mm; the size of the wooden base is Φ60 mm $\times$ 20 mm. The powder in the steel tube is ZrB_2-20SiC mixing powder, and the sum mass of the steel tube and the powder is about 28.6 g. Namely, the relative density of the loading powders is about 42% of the theory density of ZrB_2-20SiC.

During explosion, the radial pressure and impact wave appear after the front edge of the explosion wave went through. The part of the steel tube between the upper plug and the lower plug in Figure 1 is deformed. The radial velocity (v_p) of the steel tube increases with the ratio of explosive mass to tube mass (R), and it usually affects the final compact density of the ZrB_2-20SiC UHTCs.

We only measured the size change of the length and the outer diameter of the steel tubes. There were some evident scratch marks on the surface of the steel tubes after the explosive compaction; the part of the steel tube between the upper plug and lower plug was deformed radically and homogeneously. Thus, the deformation of steel tube occurred in plane and the deformation degree was decided only by the reduction of the outer diameter of the steel tubes.

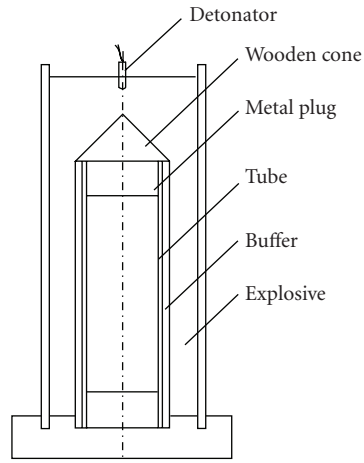

Figure 1: The set of explosive compaction.

2.2. Experiment Analysis. In the course of explosive compaction, one part of the total impact energy of the explosive is consumed on the steel tubes, and other part is consumed on the powder. Besides, there is a part of energy consumed on the air and voice. Since it is so little, it is often neglected. The common method only offers approximately, but it cannot judge the distribution of two parts of the explosive impact energy. The method in this paper can offer the effective impact energy and judge the distribution of two parts of the explosive impact energy, thus our work is essential and important.

The basic parameters in the formula include the radial velocity (v_p) of the steel tubes, the explosion velocity (v_D) of the explosive and the ratio of explosive mass to tube mass (R). The research on the explosive compaction is expressed by these parameters, because these parameters are easy to understand, moreover, these parameters are usually adopted in the specific explosive compaction experiment. The detail deduction of the formula can be seen in [12–14].

2.3. The Explosive Characteristics. We chose four kinds of explosive and all characteristics were shown in Table 1. The actual explosion velocity of the explosive is relevant to the packing density of the explosive. With the rise of the packing density, the actual explosion velocity increases, and the relationship between them is parabolic [11, 15]. Since the packing density of each explosive was lower than the theory density and the relative density was different in this experiment, the actual explosion velocity of each explosive also decreased differently. However, the range of the packing density was so small in this research that explosion velocity of each explosive could be regarded as a constant [6, 13, 14].

2.4. The Numbering Rule of the Test Samples. The test samples were divided into four groups, and each group was made of a different explosive. The letters A, N, T, and S referred to Ammonium Nitrate, Urea Nitrate, TNT and RDX, respectively. The numbers 1, 2, 3, 4, and 5 were used to show the increase of the explosive mass in turn, respectively.

Table 1: The characteristic of the four kinds of explosive.

Name	Formula	Appearance	Theory velocity (m/s)	Theory density (g/cm^3)	Actual density (g/cm^3)	Relative density (%)	Actual velocity (m/s)
Ammonium Nitrate	NH_4NO_3	Hoariness grain	3500	1.10	0.786	71.5	2800
Urea Nitrate	$CH_5N_3O_4$	White crystals	4190	1.69	0.786	46.5	3100
TNT	$C_7H_5N_3O_6$	Light yellow powder	6700	1.60	0.786	49.1	5000
RDX	$(CH_2NNO_2)_3$	White powder	8400	1.79	0.786	43.9	6000

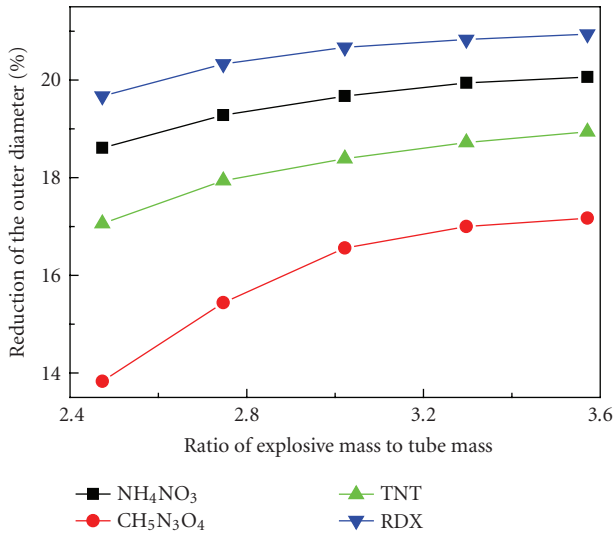

Figure 2: The relationships between the reduction of the outer diameter and the ratio of explosive mass to tube mass (R).

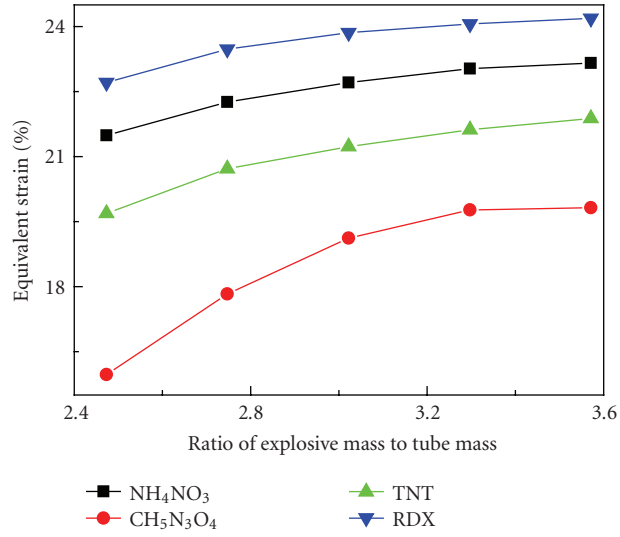

Figure 3: The relationships between the equivalent strain and the mass ratio (R).

In other words, the explosive mass was 225, 250, 275, 300, and 325 g, respectively. For example, the A3 test sample was prepared by explosive compaction using 275 g ammonium nitrate explosive.

3. The Results and the Discussion

The technological parameters and the experiment results are shown in Table 2, and Figures 2, 3, and 4 are drawn according to the relevant data. Figure 2 shows the relationships between the reduction of the outer diameter and the ratio of explosive mass to tube mass (R). From Figure 2, we can see that, with the rise of the mass ratio R, the reduction of the outer diameter changes similarly and increases gradually. Namely, the deformation of the steel tube monotonically increases with the rise of the explosive mass. It is the same when the steel tube is empty [13], but it is on the contrary to the instance of explosive compaction of the CuCr alloy powder [14]. When CuCr alloys were prepared by the explosive compaction, the steel tube hardly changed with the rise of the explosive mass.

The reason may be that during the explosive compaction of the ceramic powder, the blanks density is comparably low. With the rise of mass of the explosive, the deformation of the steel tube gradually increases, and the blanks density also increases monotonically. It perhaps does not reach the maximum. However, during explosive compaction of the CuCr alloys, the deformation of the steel tube and the compacts density both increased first, and then decreased, each of them had a maximum. However, the variation range of the density of the CuCr alloys was very small and the steel tube changed very little, too.

When compared with four kinds of the explosive, the reduction of the outer diameter of the steel tube orders from big to small as RDX, Ammonium Nitrate, TNT, and Urea Nitrate. Generally speaking, the higher the explosion velocity is, the bigger the deformation of the steel tube is. Only ammonium nitrate is an exception, and its explosion velocity is the lowest, but the deformation of the steel tube is not the smallest. On the contrary, it even exceeds the deformation made by TNT and Urea Nitrate, and next to that by the RDX explosive.

Table 2: The technological parameter and experimental results.

No.	Reduction of outer diameter (mm)	Tube deformation energy (Nm/cm^3)	Power packing density (g/cm^3)	Mass ratio (R)	Velocity of steel tube (m/s)	Explosive impact energy (Nm/cm^3)	Powder compaction energy (Nm/cm^3)	Ceramic blanks density (%)
A1	14.65	53.72	0.590	2.473	908.7	221.67	167.95	83.94
A2	14.53	55.65	0.655	2.747	951.1	269.59	213.94	86.42
A3	14.46	56.78	0.721	3.022	989.0	320.88	264.10	88.07
A4	14.41	57.58	0.786	3.297	1023.0	374.27	316.69	89.15
A5	14.39	57.90	0.851	3.571	1053.5	429.74	371.84	89.66
N1	15.51	39.93	0.590	2.473	1006.1	271.74	231.81	68.57
N2	15.22	44.58	0.655	2.747	1053.0	337.34	292.76	73.21
N3	15.02	47.80	0.721	3.022	1095.0	393.35	345.55	76.68
N4	14.94	49.43	0.786	3.297	1132.6	458.76	409.33	78.23
N5	14.91	49.55	0.851	3.571	1166.4	526.79	477.24	78.82
T1	14.93	49.23	0.590	2.473	1622.7	706.87	572.36	78.44
T2	14.77	51.80	0.655	2.747	1698.4	859.67	807.87	81.38
T3	14.69	53.08	0.721	3.022	1766.1	1023.24	970.16	83.15
T4	14.63	54.05	0.786	3.297	1826.8	1193.48	1139.43	84.38
T5	14.59	54.70	0.851	3.571	1881.3	1370.43	1315.73	85.25
S1	14.46	56.78	0.590	2.473	1947.2	1017.85	961.07	88.05
S2	14.34	58.70	0.655	2.747	2038.1	1237.95	1179.25	90.78
S3	14.28	59.65	0.721	3.022	2119.3	1473.44	1413.79	92.23
S4	14.25	60.15	0.786	3.297	2192.1	1718.52	1658.37	92.78
S5	14.23	60.48	0.851	3.571	2257.5	1973.32	1912.84	93.37

Figure 3 shows the relationships between the equivalent strains and the mass ratio R. The change tendency in Figure 3 is similar to that in Figure 2. From Figure 3, we can see that, with the rise of the mass ratio R, the equivalent strain increases monotonically. Namely, with the rise of the explosive mass, the deformation of the steel tubes increases monotonically, and the equivalent strain of the steel tubes also increases in synchronism.

Figure 4 shows the relationships among the explosive impact energy, the tube deformation energy, the powder compaction energy, and the mass ratio R in the condition of the ammonium nitrate. With the rise of ratio of explosive mass to tube mass (R), the deformation energy of the steel tube hardly changes, but the explosive impact energy and the powder compaction energy increase in synchronism. The situations of the other explosive are the same as those of the Ammonium Nitrate. With the rise of the explosive mass, the explosive impact energy increases, but the deformation energy of the steel tube does not change, thus the increased energy is totally used to compact the ceramic powder. From Table 2 we can also get that, with the rise of the explosive mass, the deformation energy of the steel tube increases, and the density of the ceramic blanks increases monotonically. Generally speaking, the higher the powder compaction energy is, the higher the density of the ceramic blank is. However, ammonium nitrate is an exception. Its explosion velocity is the lowest, and the powder compaction energy is the lowest too, but the density of the ceramic blanks is superior to that prepared by Urea Nitrate and TNT, and just inferior to that prepared by RDX.

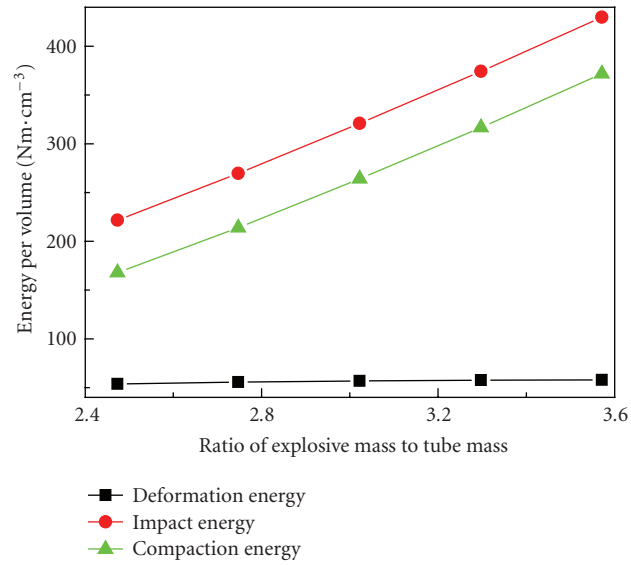

Figure 4: The relationships between the per volume energy and the mass ratio (R) in the condition of ammonium nitrate.

4. Conclusion

(1) The density of ZrB_2-SiC composites prepared by mixing and explosive compaction reaches to 93.37% of theory density.

(2) During explosive compaction, whatever kind of explosive is selected, both the reduction of the outer diameter and the equivalent strain of the steel tubes increase monotonically with rise of the mass ratio R. To the different kinds of explosive, the higher the explosion velocity is, the bigger the deformation and the equivalent strain are. Only ammonium nitrate is excepted.

(3) The explosive impact energy is divided into the tube deformation energy and the powder compaction energy. With the rise of the explosive mass, the tube deformation energy hardly changes, while the explosive impact energy and powder compaction energy increase in synchronism.

(4) With the rise of the mass ratio R, namely, with the rise of the explosive mass, the powder compaction energy increases, and the density of the ceramic blanks also increases gradually. The density of the ceramic blanks produced by different explosives orders from big to small as RDX, Ammonium Nitrate, TNT, Urea Nitrate.

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