Analysis of SiC mixture densification in explosive compaction

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Abstract. The paper presents the results of research into how the binder content and the shockwave compression parameters affect SiC and Ti powder mixture densification in explosive compaction. The microstructure of the resulting compacted metal was studied by scanning electron microscopy. Phase and chemical composition was studied by X-ray crystallography and energy-dispersive analysis. It was found that at higher silicon carbide concentrations and higher powder heating temperatures, shockwave compression reduced the residual porosity of the compacted metal to 2%. The microstructure was a carbide-silicon matrix with titanium inclusions. The obtained material matched the initial components in phase composition.

1. Introduction

Silicon carbide products have a wide range of use in a variety of industries. SiC products have outstanding properties making them a good candidate material for internal combustion and gas-turbine engine parts, abrasive tools, ceramic bearings, nozzles and burners, tooling for annealing the ceramics, chemically resistant heavy-duty parts, heaters for high-temperature furnaces, armor plates, etc.

SiC materials are classified by the production method (and thus by properties) as follows:
(a) porous materials:
   – carbon-bonded silicon carbide (CSiC),
   – recrystallized silicon carbide (RSiC),
   – reaction-bonded silicon carbide (RBSiC);
(b) high-density:
   – siliconized (reaction-bonded) silicon carbide (SiSiC),
   – sintered silicon carbide (SSiC),
   – liquid-phase sintered silicon carbide (LPSSiC),
   – hot-pressed silicon carbide (HPSiC)
   – hot isostatically pressed silicon carbide (HIPSiC) [1].

Each of the materials has certain advantages and disadvantages, as does its associated method. This is why it might be of interest to carry out feasibility tests of a novel SiC production method, which is referred to as explosive compaction [2] and enables powder consolidation during compaction [3]. The method does not rely on sintering for making workpieces; instead, it utilizes unconventional binders like titanium, which in some cases significantly improves the characteristics of the output materials, e.g. their tribotechnical properties [4]; this is why it seems particularly relevant.

Whether the fundamental opportunities provided by using explosive compaction for making SiC materials can be grasped depends on whether their components are effectively densified while preserving the original phase composition that might be altered by their chemical interaction in shockwave compression or subsequent cooling.
This is why the goal hereof is to study the densification, structure, and distribution of chemical elements between the components of solid SiC-Ti alloys produced by explosion, and to identify the prevailing factors that could enable making virtually poreless materials during compaction.

2. Materials and methods
The research team used SiC powders with a titanium binder. The binder content was 26%, 37%, 48%, and 58% by weight or 20%, 30%, 40% and 50% by volume.

Explosive compaction followed the chart in figure 1a: the original SiC and Ti mixture was placed directly on the steel substrate and exposed to a normal-incidence plane wave through an intermediate pad that separated the detonation product from the powder.

Compression parameters were calculated by the (P, u) diagram method based on finding the parameters of incident and reflected waves by analyzing the intersections of impact-related adiabatic curves of the pad, powder, base, and detonation products in pressure and mass velocity coordinates [5]. The loading process parameters were adjusted in such way as to vary the shockwave compression heating temperature within 700÷840°C and the pressure within 11.5 to 16.5 GPa by altering the explosive charge height [6].

Structure and chemical composition of phases were studied by optical and scanning electron microscopy using a Carl Zeiss Axiovert 40MAT metallographic microscope and a FEI Versa 3D SEM featuring an integrated focused ion beam system for foilmaking and an energy-dispersive electron microprobe system, EDAX Apollo X. For X-ray crystallography, the researchers used a Bruker D8 Advance diffraction meter. Phases were identified by Diffrac.EVA (version 4.2.1), a piece of software that had come with the diffraction meter, using the licensed Powder Diffraction File-2 database (the International Center for Diffraction Data). Residual porosity was used as a densification quality meter and was found using ImageJ v1.52 on unetched foil.

3. Results and discussion
Tests have shown that explosive compaction of SiC and Ti powders may occur without their possible chemical interaction [7] despite significant heat buildup in shockwave compression, see figure 2. The porosity of the resulting materials is a function of binder content and loading parameters; as such, it may vary significantly, see figure 3.
Greater shockwave compression pressure reduced the porosity for any of the tested compositions. However, unlike in case of well-studied Cr$_3$C$_2$-Ti materials [5], low binder content did improve densification, i.e. the high-hardness carbide component improved rather than worsened the compressibility of the original power mixture, see figure 4.

This might be for at least two reasons.

The first only logically follows from analysis of compacted structures. As shown in figure 3b, titanium particles preserve their shape after compaction in SiC, making isolated inclusions in a continuous SiC matrix. At the same time, SiC-Ti powder components behave unusually compared to Cr$_3$C$_2$-Ti materials, where the metallic binder forms a continuous matrix [5]; this might be due to abnormally fast propagation of sound in silicon carbide resulting in a faster propagation of compression waves across the SiC particle frames than across their Ti counterparts. As a result, SiC particles are moved first and travel to the pores in the original powder mixture, see figure 5a; this results in a greater densification of mixtures that originally have more SiC and pores.

This assumption is further proven by the fact that in “$\varphi$ - P·($\varphi_0$·[SiC])” coordinates (where $\varphi_0$·[SiC] is a value directly proportional to the probability that the SiC particles have free surface in the original mixture and are thus able to move), experimental data fit one curve, see figure 5b.
The second reason can also be identified from the structural analysis of the resulting materials, which shows that SiC particles in a carbide-silicon matrix are significantly pro-deformed, enabling their tighter interface, see figure 6.

**Figure 4.** Residual porosity $\varphi$ of SiC-based composites of varying Ti content as a function of the maximum compressive pressure $P$ in shockwave treatment.

**Figure 5.** Densification model of (a) SiC-based composites of varying Ti content and residual porosity $\varphi$ as a function of the maximum shockwave compression pressure $P$, initial porosity $\varphi_0$, and [SiC] content (b).
SiC deformation requires temperatures above 780°C corresponding to 0.35·T_{melt}. SiC and is the lower boundary where ceramic and semiconductor phases, including SiC, begin a transition to a plastic state [8]. However, analysis of the experimental compression conditions shown in figure 7 shows that the required temperatures are not always attained; thus, greater titanium binder content in the original powder lowers the chance to attain such temperatures, thus reducing the maximum expected densification.

4. Conclusions
Explosive compaction of SiC and Ti powder mixtures where the metal binder concentration ranges from 20 vol.% to 50 vol.% results in the greater densification, the more carbide-phase the powder contains and the higher heating temperature shockwave compression attains. The material can be made virtually poreless without sintering. It is possible to preserve the two-phase initial state of SiC and Ti powders at loads sufficient for maximum densification. The structure of the resulting materials is a carbide-silicon matrix with titanium inclusions.

Acknowledgements
Financial support was provided by the Russian Science Foundation (Grant 18-19-00518).

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