Durable SiC Honeycomb Dies for Kiesel Fuel Emission with Electron Beam Irradiation

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Abstract – In this paper, stress analysis and surface modification on DPF honeycomb dies made of tungsten carbide is conducted to overcome the problem of fracture and wear of the dies. Stress analysis results show that effect of K_{IC} is dominant on the fracture of dies. To reduce the wear, the surface of the dies is modified by using electron beam irradiation with copper. After the beam irradiation, the copper can be melted inside the die holes, to provide streamlined shape in the holes. It is also obviously shown by SEM that due to copper layer, the defects between the grains can be filled up by the copper, which may avoid pullout of the WC grains from the surface during the extrusion process.

1. Introduction

Nowadays, the most common way to achieve high particulate reduction is to use filters that trap exhaust particulates called as Diesel Particulate Filter (DPF). DPF can also reduce visible diesel smoke and can reduce odor. With the tightening of environmental regulations, the demand for exhaust-gas purifiers for diesel-powered automobiles has been increasing.

Silicon carbide is usually used as materials for the DPF honeycomb because of its property as high-temperature material, and through various ingenious ideas it can be formed into a porous solid. For producing green body of the honeycomb before sintering process, the DPF honeycombs should be formed from extrusion process of SiC paste through a die made of tungsten carbide. However, since SiC particles are relatively high hardness material, there are two main problems of the DPF dies in the SiC extrusion process. Firstly, there is problem of fracture failure of the die due to the use of brittle material for the honeycomb die (tungsten carbide with low content of Co binding). Secondly, due to high hardness of the SiC particles, the surface of the die can be worn out, resulting in change of initial slit dimension of die.

Several attempts have been tried by many researchers to solve the problem of fracture and wear. One of the attempts is using combination of two different materials in manufacturing of the die. The die for forming the honeycomb structure is provided by a die with two parts, one part is die base with intersecting slits in array shape, where extruded SiC comes out, and the other part is die base with many holes connected to the slit, where the forming material is introduced. The report combine tungsten carbide super hard alloy for the slit part to achieve good wear resistance and steel for the inlet part [1]. Other method involves forming slots in the steel die and then applying a uniform coating of hard material such as iron boride, chromium carbide, aluminum oxide, titanium carbide, titanium nitride or titanium carbonitride on the slit surfaces [2] or TiCN layer on the plating layer by means of CVD (chemical vapor deposition)[3].

In this work, we use the same material for whole part of the die that is tungsten carbide, which is considered as having high wear resistance. Another advantage is that there is no necessity of brazing or combining separated parts of die. However, because tungsten carbide is a brittle material, fracture failure will be important factor to be taken into account. Increasing fracture toughness of the material, on the hand, only can be provided by material with lower wear resistance. This report will discuss the reason of fracture and propose surface modification on die made from WC-Co to reduce wear of the die during the extrusion process.

2. Experimental Procedure

To evaluate the structural design of honeycomb die made of tungsten carbide materials, finite element method is conducted for analyzing the maximum stresses exerted on the die. The analysis is carried out at St. Petersburg State Polytechnic University Mechanics and Control Processes Department. The FEM analysis is performed in 3D by using commercial software of ANSYS LS-DYNA. Due to symmetrical shape of the sample, the model is represented by 1/4 of real shape, with mesh number of 160.000. For the stress calculation, pressure on the inlet surface (surface where there are holes) is assumed to be 10MPa, which is distributed homogenously on the die surface.

The task is to calculate stress during the extrusion process. The calculation of maximum stresses is required to evaluate the reason of the fracture on die made of WC-Co. In our experience, WC-Co G55 (Fujilloy) is more vulnerable to failure compared to G65. We evaluate the two kinds of tungsten carbide with different mechanical properties shown in Table 1.

The next task is to make surface modification with Cu layer on the honeycomb die made of WC-Co. The purpose of surface modification is to reduce wear on the surface during the SiC extrusion process. Actually, the idea is not to make the surface high in hardness, but to make low friction during the extrusion of SiC paste. Copper is known as material which can be coated on WC-Co to obtain low friction coefficient [4].

The Cu layer is produced by using SOLO electron beam irradiation system SOLO (Nagata Seiki Co. Ltd. Japan). Before the irradiation process, copper tubes made from 0.1 mm foil are inserted into holes of the honeycomb die. The irradiation condition is presented in Table 2. To obtain homogeneity of treatment, the sample is rotated along its center with speed about 60 rpm.

Table 1. Tungsten carbide material properties

Material	Hardness (HRA)	Tensile strength MPa	Compressive strength MPa	KIC $MPa \cdot m^{1/2}$	Wear $\times 10^{-5}$ cm^3/rec (ASTM)
G55	88.5	1720	4610	12	12
G65	86.5	1670	3920	18	18

Table 2. Electron beam irradiation condition

Beam Parameters	Values
Beam current	40 A
Acc. Voltage	19 kV
Frequency	10 Hz
Number of pulses	1000 x3
Solenoid current I1	6.3 A
Solenoid current I2	9.9 A
Pulse duration	200 ms

3. Results and discussion

3.1. Maximum stress calculation

Result of the finite element analysis (FEA) is shown in Fig. 1 below. Maximum tensile stress calculated from finite element method is 717 MPa which exerts on the center of the die. The stress is much lower than the tensile strength of tungsten carbide materiall(Tabel 1). Maximum compressive stress calculation result is 544 MPa, which is also less than compressive strength of the material.

According to FEA results, the stresses during SiC extrusion are low enough, which will not be the cause of fracture, even for dies made of copper alloy (PROTHERM, Uddeholm) or powder metallurgy stainless steel (ELMAX, Uddeholm). Table 3 shows the stresses obtained from FEA compared with the strengths of each material.

Tungsten carbide is a brittle material which can be easily broken by low load. For brittle materials, fracture is mainly generated due to the low fracture

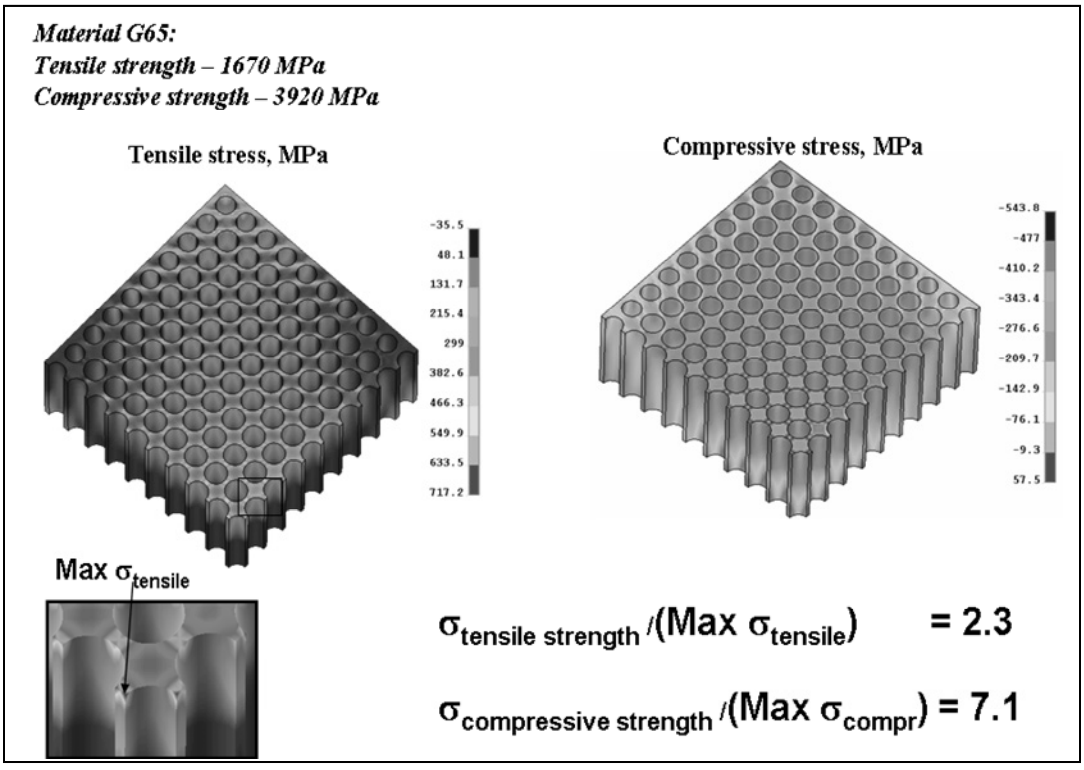


Fig. 1. Finite element analysis of honeycomb die made of WC-Co. Tensile strength and compressive strength both are higher than the stresses calculated by finite element method

toughness of the material. The toughness of a material is described as the load (per unit area) required for initiating a crack when this load is applied to a surface. A measure of the fracture toughness of a material is the Critical Stress Intensity Factor (K_{IC}). Considering the shape of flaw of the die, critical stress is calculated by the following equation [5]:

$$\sigma_c = \frac{K_{IC}}{Y\sqrt{\pi a}}. \quad (1)$$

Where σ_c – critical stress, K_{IC} – fracture toughness factor, Y – 0.73 for a half-circular surface crack in the die, a – flaw size (0.197 mm).

Table 3. Comparison of stresses obtained from FEA and strength of each material

Material	Max tensile stress MPa	Max Compr. stress MPa	Tensile strength MPa	Compressive strength, MPa
WC-Co G65	717	544	1670	3920
ELMAX	712	528	1460	3000
PROTHERM	717	543	790	640

Calculating the critical stress of the tungsten carbide material with K_{IC} values written in Table 1, we can obtain critical stress in case of G55=634 MPa, which is less than the maximum tensile stress obtained from finite element analysis result (about 700 MPa). Since the real maximum tensile stress exceeds the critical stress, it will be reasonable why G55 is vulnerable to failure. For G65, the critical stress can be as high as 993 MPa, providing enough toughness to prevent fracture. The application of G65 WC-Co is more suitable to avoid the fracture failure.

3.2. Copper layer surface modification

The remaining problem of G65 application is wear resistance of the material. As shown in table 1, the wear amount of G65 is higher than wear amount of G55. It implies that surface modification to reduce wear on G65 is required. Surface modification with Cu layer has been carried out for solving this problem.

Figure 2 shows an advantage of Cu layer in the hole of die. After the electron beam treatment, Cu is melted to fill up the corner of the hole. It can modify the shape to make streamlined flow of SiC paste during the extrusion process. In the initial shape, the hole has relatively sharp corner which will result in higher stress on wall of the hole.

Assuming a similar process during SiC extrusion, the Cu treated surface was polished with sand paper #1000 containing SiC particles. Figure 3 shows the SEM picture of the Cu treated (b) compared with the initial slit surface (a). It is obviously shown that the defects between the grains, which appear in the initial surface, can be filled up by the copper as shown in Fig. 3, *b*. The combination of Cu and WC grain may reinforce WC grains to avoid pullout of the grains from the surface during friction process.

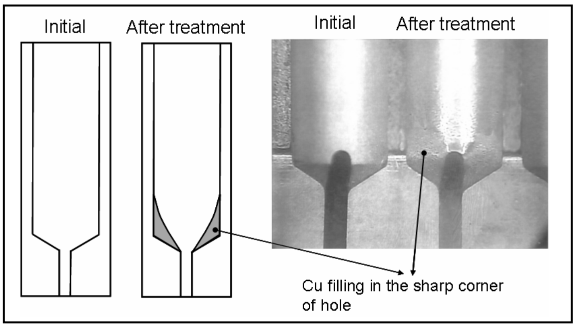
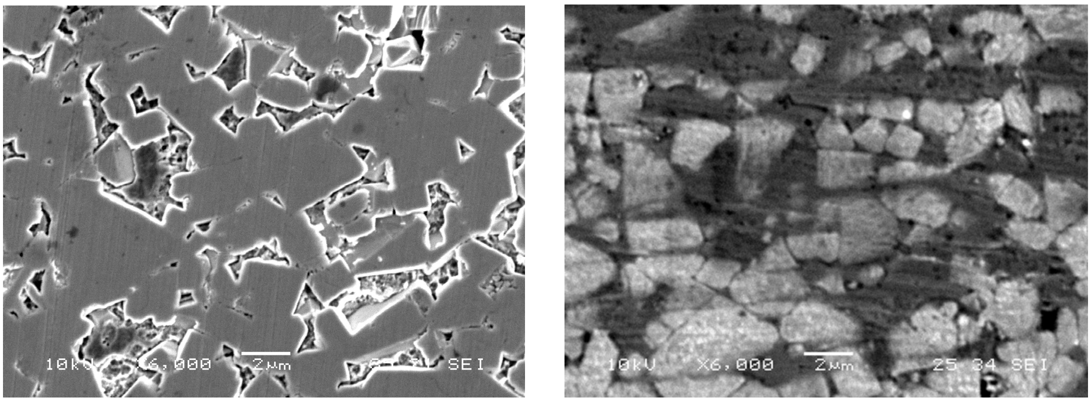


Fig. 2. After EB melting, some accumulations of Cu remain in the sharp corner of the hole. It may provide a streamlined shape which can perform laminar flow during SiC extrusion

During the SiC extrusion process, the slit surface of WC-Co die will have severe friction contact with the SiC particles. In case of many defects exits on the



(a) Initial (b) Cu treated

Fig. 3. Surface of the initial WC-Co die (a), and after Cu treatment (b). From the SEM picture, it can be shown that the defects between the grains can be filled up by the copper

surface as shown in Fig. 3, *a*, wear of surface will be occur more easily due to higher shear stress exerting on the surface. It is expected that the Cu filling in the defects will decrease wear of the surface of the die.

4. Conclusions

1. Stress analysis and surface modification with Cu layer have been performed to overcome the problem of fracture failure and wear in the DPF die.
2. The stress analysis results show that the effect of K_{IC} is dominant on the fracture of dies.
3. Copper layer on the honeycomb die manufactured by using SOLO electron beam irradiation can be used to modify the holes of the die to be streamline shape for reducing stress from SiC paste during the extrusion process.
4. The defects between the grains can be filled up by the copper after surface modification with electron beam. The modification of the WC-Co surface may increase the life time of the DPF die.

Acknowledgments

The authors would like to express their thanks to A. Rubsthein, K. Shalnov, S. Gregoriev and V. Kukhta for their help to conduct experiments and observations in this study. Special thanks is also directed Mr. Hiroshi Koike from IBIDEN Co., Ltd. who has supplied the samples for the present study.

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