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# Transpiration cooling during ultra-high temperature erosion

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ABSTRACT

In present study the static firing of the bi-propellant engine has been employed to investigate the transpiration cooling phenomenon of W-Cu materials during ultra-high erosion against liquid alumina droplets. For this purpose, two samples of W-10 wt% Cu composite were prepared by sintering+infiltration method. The erosion test carried out at 3000 °C for 40 s at the alumina droplet speed of 1200 m $s^{-1}$. Two incident angle of 0° and 30° selected to study the effect of erosion angle on transpiration cooling. The microstructure evolutions were studied by SEM and EDS. The obtained results exhibited that erosion at 30° resulted in higher deposited alumina layer as well as lower erosion rate.



## 1. Introduction

W-10 wt% Cu is widely used in aircraft propulsion systems and space thermal protection systems because of its high strength at elevated temperature, high resistance to thermal shock and ablation resistance [1]. This composite often employs an efficient cooling technique such as transpiration cooling through the combustion chamber and throat section of the engine [2]. Then, W-10 wt% Cu composite must be fabricated only by infiltration of copper into a porous tungsten skeleton [3]. Copper is a good coolant material having excellent properties such as high thermal conductivity and low density and can be used in such applications involving heat exchanging [4]. When applying transpiration cooling of copper to a porous tungsten skeleton, a coolant film may be formed over the surface thickening the boundary layer and therefore reducing the temperature of the skeleton wall [5]. Due to multiple cooling channels within the porous tungsten skeleton, the transpiration cooling depth as well as the incident angle play a critical role in erosion behaviour. Based on S. Borji et al. [6], The erosion rate increases slightly with decreasing transpiration cooling depth. It is found that, the specimen containing Ni activator exhibit about 33% lower erosion rate compared to conventional prepared specimen due to higher transpiration cooling depth. On the other hand, Impact angle or incident angle is defined as the angle between the target material and the trajectory of the erosive alumina droplets. Ductile materials exhibit a maximum in the erosion rate at intermediate impact angles [7,8]. In contrast, the maximum erosion rate of a brittle material is usually obtained at normal impact angle [9].

In this paper, the effect of impact angles of 0° and 30 °C on the microstructural evolution and erosion loss of W-10 wt% Cu composite was investigated. Also, it is tried to discuss the skeleton change related to transpiration cooling mechanism.

## 2. Experimental method

In this work, W powder with average particle size of 6 μm was used as raw materials. Green compacted blocks have been made using Cold Isostatic Press at pressure of 180MP. Subsequently, green compacts were sintered at 2150 °C for 180 min to reach apparent density of about 80 ± 2 vol%. Infiltration of tungsten skeleton was carried out at 1300 °C for 120 min in hydrogen atmosphere. Sintering and infiltration was done at the heating rate of 10 °C/min in tungsten resistant furnace. The densities of sintered and infiltrated compacts were measured by the Archimedes method. The main purpose of tins study is investigation the erosion behavior and transpiration cooling due to liquid alumina particle erosion by static firing of the bi-propellant engine. Two incident angles of 0° and 30° were in erosion test for 40 s. The test temperature and alumina droplets velocity selected about 3000 °C and 1200 m/s, respectively. Erosion was measured by means of a profile projector. SEM was used for studying the detailed microstructure of specimens. Also, composition of eroded surfaces was characterized using EDS analysis.

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## 3. Results and discussion

In the W-10 wt% Cu composite prepared by infiltration, penetration of copper through porous tungsten skeleton can be occurred due to capillary force as well as high wettability of tungsten particles by liquid copper [10,11]. Then, all of the pores in the sintered skeleton must be open and inter-connected. It provides a rapid transport path for molten copper, so improves the erosion behavior of tungsten skeleton. Fig. 1 exhibits SEM micrographs of porous tungsten skeleton with inter-connected porosity network, before and after infiltration. Existence of inter-connected porosity network is critical for achieving a suitable transpiration cooling system during erosion.

When the firing gases heats the wall of infiltrated composite, Cu begins to melt and can be evaporated due to the high temperature of erosion test. In this condition, no any changes take place for tungsten skeleton. With consuming of inner copper phase during transpiration cooling, the temperature of the skeleton wall increases with time and the bulk expansion of Cu can take place, and then liquid Cu will flow to the surface along the capillaries to form surface films which can act as heat insulation layers. With continuous firing, gas-liquid interface moving from the surface to inside, Cu will diffuse into the gas layer as liquid or gas state and absorb heat. When the gas-liquid interface move enough from the exposure surface, the transpiration cooling mechanism will be stopped and ablation of skeleton wall takes place. By removing a layer of tungsten particles, the distance between eroding surface and gas-liquid interface will reduce and transpiration cooling resumes again. Fig. 2(a) shows optical micrograph of eroded specimen which verifies formation of a copper-free skin due to transpiration cooling mechanism. Also, the results of elemental map and EDS analysis are shown in Fig. 2b. As illustrated, due to transpiration cooling mechanism, the weight percent of Cu reduces by decreasing the distance from exposure surface. These results indicate that molten copper was able to flow toward the eroding surface and takes part in transpiration cooling. Once the flowing liquid copper reaches to hot wall of skeleton, begins to evaporate and consume the heat generated by fuel burning. In this condition, evacuated porosities may be created beneath the exposure surface. It is necessary for skeleton to maintain its inter-connected porosity network for continues liquid copper flow outward the surface. Generally, it can be distinguished three different copper phase state during erosion at ultra-high temperatures. In the regions near to eroding surface (region I in Fig. 2b), the copper phase will be in gas state due to impact with hot explosion gases. It resulted into formation of entirely evacuated porosities in this regions (Fig. 2a).

With increasing the distance from surface (region II in Fig. 2b), a continues flowing of molten copper can be expected. This flowing rate is related to the radious of porosity channels, thermal conductivity of tungsten skeleton, distance from eroding surface and incident angle. Due to consuming of copper liquid, this region consists of filled and evacuated porosities [4]. With further increasing the distance from exposure surface (region III in Fig. 2b), the temperature falls to lower than melting point of copper. Therefore, copper phase keeps its initial state and remain in solid phase. However, the effect of copper evaporation on the cooling of skeleton wall is attributed to transpiration cooling depth. The prepared W-10 wt% Cu composites in this study exhibited a transpiration cooling depth equal to 6 mm.as mentioned previously, current studying erosion is caused on solid W-Cu composite by the impacting action of liquid alumina. These erosive particles are carried by a hot gas stream. The angle of incidence of the particles influences the erosion rate substantially, and can change the erosion mechanism. The SEM images from specimens after erosion test at two different impact angles (0° and 30°) are illustrated in Fig. 3. It can be seen in impact angle of 30°, the erosion mechanism mainly consists of inter-granular fracture of the tungsten skeleton. This failure mechanism demonstrates the brittle erosion behavior of infiltrated W-10 wt% Cu composites. Additionally, some evacuated porosity related to transpiration cooling can be distinguished in Fig. 3a, b. Brittle materials exhibit an erosive wear mainly due to the chipping. The material removal occurs with the formation of fractures. The erosive alumina droplets remove material by chip formation, essentially scraping material off the surface of the solid in a manner similar to machining [1,2,6].

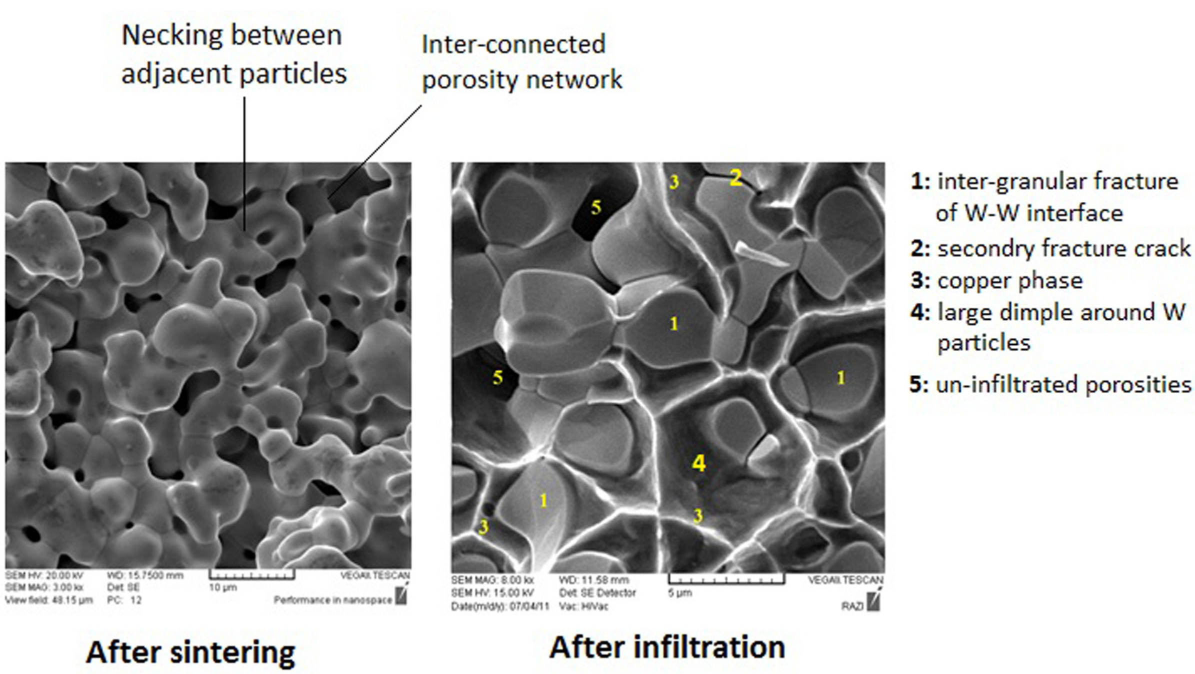


**Fig. 1.** SEM micrographs from porous tungsten skeleton before (left) and after infiltration (right).