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Methods of Increasing Thermal Conductivity of Plasma Sprayed Tungsten-Based Coatings

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Abstract/Introduction. Tungsten is the main candidate material for the armor of plasma facing components for ITER and future fusion devices [1]. Plasma spraying is an alternative method for manufacturing tungsten-based coatings, including composites and graded layers, having a number of advantageous features [2]. On the other hand, the main limitation to application of these coatings on high heat flux components, is their low thermal conductivity, originating in the layered structure [3]. This paper is focused on four methods of improving the coatings' thermal conductivity. First method consists in modification of the basic spraying parameters, which have a direct influence on the coating structure and therefore properties. The other three methods involve post-processing of the coatings: molten copper infiltration, laser remelting and densification by HIPping. The latter encompasses also tungsten-copper composites of various compositions. Experimental results, including structural and thermal characterization, are presented for each method. Finally, the applicability of these methods, from the point of view of manufacturing the plasma facing components, is discussed.

Experimental

All coatings were sprayed in ambient atmosphere by water stabilized plasma torch (WSP®), using W or W+WC and Cu powders. Several post-processing methods were applied; details are provided either below or in the references. Composition and porosity of the coatings were assessed by image analysis on back-scattered electron images from SEM. Thermal conductivity was measured by the xenon flash method in the 100-400 °C range, using ~1 mm thick free-standing coatings removed from the substrates

Spraying modifications

Air plasma spraying of tungsten is complicated mainly by its high melting point (3400 °C) and in-flight oxidation. During the development of spraying by the water stabilized plasma torch, a number of spraying parameters were adjusted to reduce the negative effects of the above factors. In-flight particle diagnostics was used to aid in the optimization; details can be found in [3,4]. The following adjustments were found to improve the coatings over the initial settings:

- proper selection of feedstock powder size (smaller powder is easier to melt, but has higher specific area available for oxidation)
- reduced injection distance and spraying distance, leading to higher particle temperatures before impact
- admixture of WC powder, which creates an auto-shrouding effect, limiting the oxygen access to tungsten.

Despite significant reduction of coating porosity and oxide content, the thermal conductivity improved only moderately, staying in the range of 10-40 W/m.K. More significant improvement (up to 85 W/m.K) was achieved using hybrid torch, using a mixture of water and argon for the plasma. The resulting plasma jet is characterized by lower temperature gradients and more efficient particle acceleration, both of which seem favorable for spraying of tungsten. The in-flight oxidation problem could be eliminated by spraying in vacuum [5], however, this is rather expensive and limited to low-power torches, with low deposition rate.

Laser remelting

Laser remelting was performed in order to reduce the coating porosity and the intersplat interfaces which hinder the heat transfer. Experiments were carried out on pure tungsten coatings, using a 550W Nd-YAG pulsed laser at Czech Technical University. A number of parameter combinations were tested on single traces: mainly pulse frequency, pulse length, laser power and traverse velocity. These resulted in a variety of surface modifications, from incomplete localized melting to contiguous melt pool, to erosion and melt ejection. From the observations, the most promising conditions were chosen for area scanning. Due to low laser power, the remelted layer was only about 0.3 mm (out of 1 mm coating), Fig. 2. Despite this shallow zone of influence, thermal conductivity improvement from 11 to 15 W/m.K was observed. Deeper melting can be expected with a laser having a higher power and/or more favorable wavelength for absorption.

Fig. 1. Laser remelted coatings. a) single trace, top view, b) single trace, cross-section, c) area scan, top view.

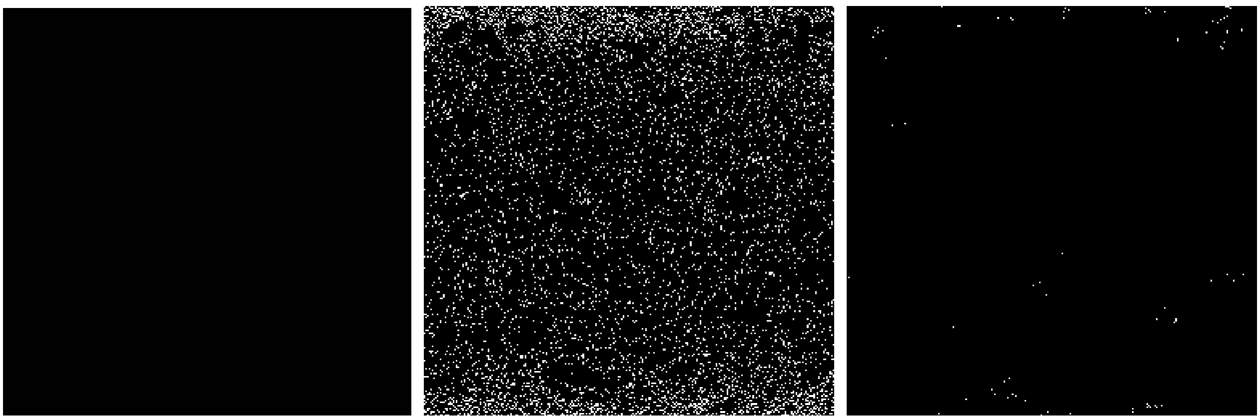


Fig. 2. Cross-section of the copper-infiltrated tungsten coating. a) back-scattered electron image, b) tungsten map, c) copper map.

Copper infiltration

Plasma sprayed tungsten coating was infiltrated by molten copper. Copper powder was placed on the coating surface and melted at about 1100 ^{o}C in an induction furnace under hydrogen atmosphere [6]. Very good filling of the pores by copper was observed by elemental mapping, see Fig. 2. Thermal conductivity of the as-sprayed coating was 13 W/m.K at RT and 24 W/m.K at 1000 ^{o}C. The infiltrated coating had conductivity 107 W/m.K at RT, which represents a significant increase.

HIPping

W+Cu composites of five compositions were sprayed by WSP [7] and subsequently densified by hot isostatic pressing at the Institute of Materials and Machine Mechanics. The HIPping conditions were 1000 ^{o}C for 120 min, 140 MPa. Two configurations were used – open-HIPping and closed in a copper capsule. In all cases, porosity was significantly reduced (Fig. 3, Tab. 1). Thermal conductivity increased 2-8 times, depending on composition. Expectedly, higher increase was observed for the copper-rich samples, due to its lower melting point. Larger improvement was achieved by encapsulated HIPping (Fig. 4), where the gas retained in the pores was evacuated. The particles in the as-sprayed copper coatings had a range of non-stoichiometric oxygen content; after HIPping, this segregated into isolated Cu_2O particles in pure Cu matrix (Fig. 3).

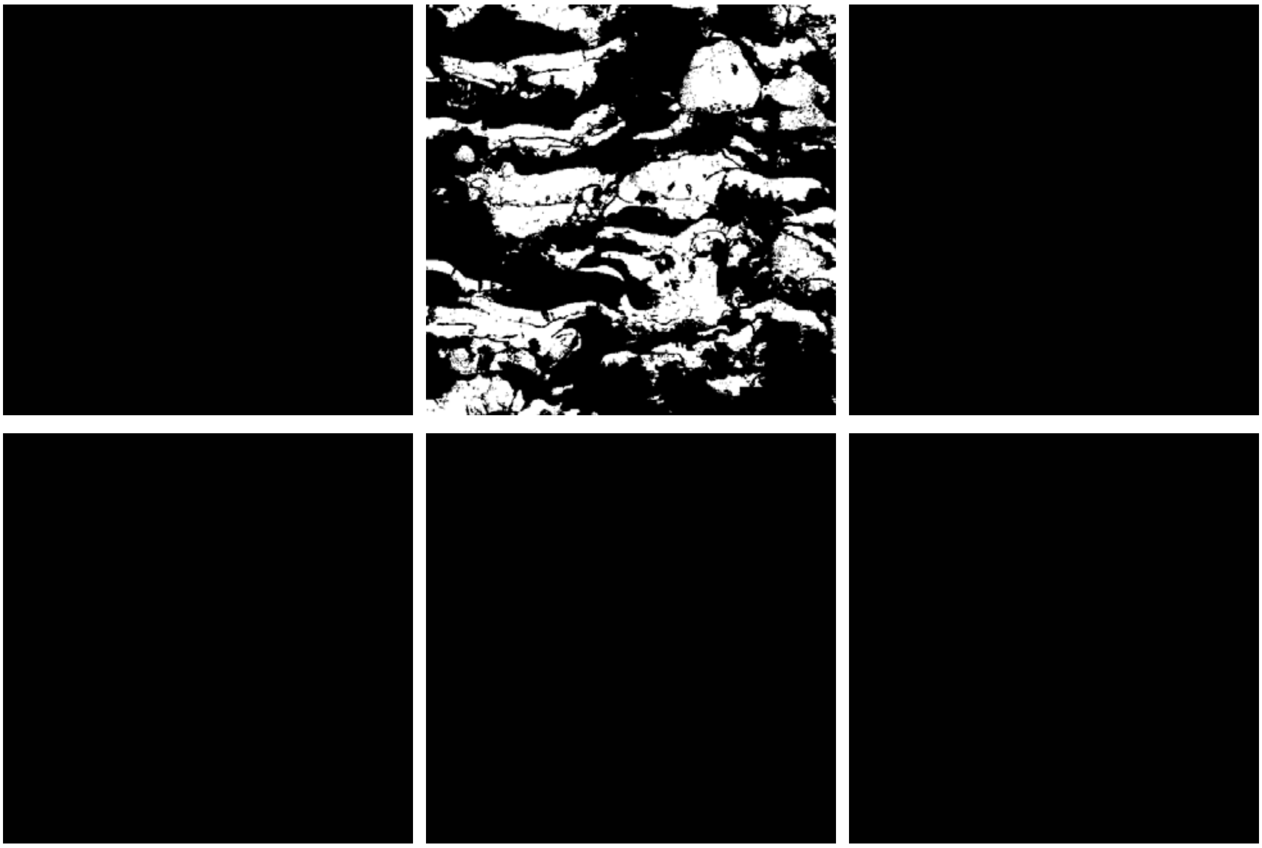
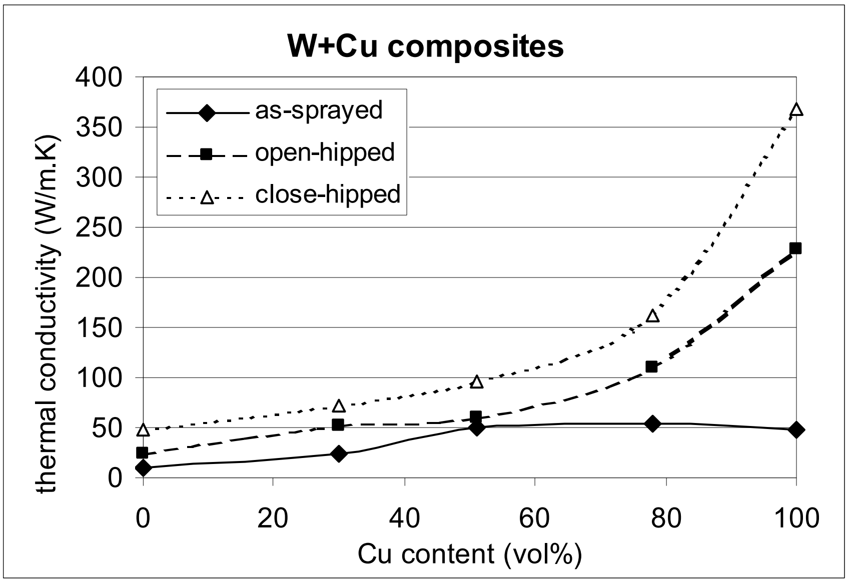


Fig. 3. Detailed cross-sections of the pure Cu, W+Cu 50/50 and pure W coating (left to right) in the as-sprayed state (top row) and after encapsulated HIPping (bottom row).

nominal W content	0	25	50	75	100
observed W content	0	22	49	70	100
porosity (as-sprayed)	2	10	3	5	9
porosity (open-HIPped)	0.6	0.2	0.3	0.7	0.9
porosity (close-HIPped)	0.05	0.03	0.08	0.11	2.56

Tab. 1. Composition and porosity (in %) of the W+Cu coatings. The porosity levels should be taken as orientational only, as they might be influenced by the metallographic preparation.



Thermal conductivity vs. composition of as-sprayed, open-hipped and close-hipped coatings at 100°C. The same trends were preserved at higher temperatures.

Conclusions

Four methods were considered for improving thermal conductivity of plasma sprayed tungsten-based coatings. Modification of the spraying parameters is the most applicable to component manufacturing, however, the conductivity improvement is only moderate. More experiments with the promising hybrid torch are underway. Laser remelting is also a promising method, but needs to be verified with a higher-power equipment to achieve deeper melting. HIPping of the coatings achieved the highest increase in conductivity. However, both HIPping and copper infiltration would be difficult to apply to real components due to copper melting involved. A potential alternative would be a separate processing of free-standing coatings and subsequent joining to the parts, e.g. as stress-relieving interlayers.

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