

tion, reductive carbonylation, carboxylation, reductive carboxylation, reductive coupling, condensation, cracking, hydrocracking, cyclization, cyclooligomerization, dehalogenation, dimerization, epoxidation, esterification, exchange, Fischer-Tropsch, halogenation, hydrohalogenation, homologation, hydration, dehydration, hydrogenation, dehydrogenation, hydrocarboxylation, hydroformylation, hydrogenolysis, hydrometallation, hydrosilation, hydrolysis, hydrotreating (HDS/HDN), isomerization, methylation, demethylation, metathesis, nitration, polymerization, reduction, reformation, reverse water gas shift, Sabatier, sulfonation, telomerization, transesterification, trimerization, and water gas shift. Combustion is another preferred reaction. Hydrocarbon steam reforming is especially preferred (such as methane, ethane or propane steam reforming).

EXAMPLES

[0322] Uniform Coatings in a Multichannel, Microchannel Device

[0323] A microchannel device (FIG. 10) having 48 sets (4×12) of parallel channels, with each set consisting of 5 individual channels. The device is designed for steam reforming of methane (SMR) and contains an integrated combustor (Fuel, Air and Exhaust for the combustion and Reactant and Product for the SMR). The device is over 20 inch (50 cm) long, making the aluminidization circuit over 40 inch (1.0 m) long (Exhaust connected to Fuel and Air, Product connected to Reactant). The Fuel and Air channels are in communication via an array of jet holes in each pair of channels.

[0324] The SMR channels were blanketed off with an argon flow while channels in the combustion circuit were aluminidized. Calculations showed that the flow of aluminidizing gas through the microchannels was highly non-uniform with flow rates in some channels 10 times greater than others, while the surface area within each microchannel was relatively similar. This difference in flows is due to the complex design of the channels and manifold region, where the flow distribution design was developed for flows during operating conditions (much higher flowrates by more than 10×) than the low flowrates used during the aluminidization process. The CVD vapor flow was fed from the exhaust manifold, flowed through the exhaust channels, through a u-bend and then into the fuel and air channels and exited through the fuel and air manifolds. After aluminidization, the device was cut open and various channels were inspected by SEM. Cross-sectional samples were viewed at the midpoint of the device (FIG. 11) and near one end—this end is both near the start of the aluminidization circuit (exhaust channel) and the near end of the aluminidization circuit (air and fuel channels), FIG. 12.

[0325] From the SEM data it can be seen that the aluminide coatings were highly uniform both along the length of each channel as well as channel-to-channel, despite the large difference in channel-to-channel flow rates. In each case, coating thicknesses appeared to be within about 10%. Additionally, the coatings appeared to be essentially defect-free.

[0326] Coatings at Corners

[0327] Interior corners of microchannel devices were inspected by SEM. These devices were again Inconel™ 617

coated with an aluminide layer. Sharp ($90\pm 20^\circ$), well-formed corners coated with an aluminide layer were surprisingly found to have conformal coatings (see FIG. 13a) with a sharp angle at the interface between the channel's interior (dark area) and the aluminide coating. For purposes of measuring the angle of the coating, the angle of the coating is based on averaging surface roughness for 100 μm along each edge from the corner. In some preferred embodiments, the angle of the coating is $90\pm 20^\circ$, in some preferred embodiments $90\pm 10^\circ$. Another measure is the thickness $((d1+d2)/2)$ of the coating at the perimeter of the corner coating (see FIG. 13b) based on extensions (d1 and d2) of the same 100 μm lines used to measure coating angle; preferably this thickness of the coating at the perimeter of the corner coating is within 25%, more preferably within 10% of either the average coating thickness (averaged over a microchannel wall, or 100 μm microchannel wall segment, terminating at the corner), or within 25%, more preferably within 10% of either the midpoint thickness (measured at the midpoint of a microchannel wall, or microchannel wall segment, terminating at the corner).

[0328] Crack filling is shown in FIG. 14. In this example, the Inconel sheets were stamped. The stamping process tends to result in slightly curved edges, and these curved edges can result in gaps at the corners formed between two laminated sheets. The aluminide coating fills this gap, again this occurs in a conformal fashion with the thickness of the coating being uniform with elsewhere on the microchannel up until the point that the gap is filled and the coating can no longer grow. In other words, thickness appears to be limited by distance from the metal substrate.

[0329] Multichannel Sol Coated Device

[0330] A microchannel test device with 48 sets of channels was prepared with post-assembly coatings and tested. The device was made from sheets of an Inconel™ Ni-based superalloy. An aluminide layer was formed over the alloy. Then it was oxidized (as described above) to form an alumina layer. Several solution-based coatings were applied. To apply the coatings, the device was oriented on one end (the straight microchannels were oriented parallel to gravity), and, in each step, the liquid was added through an inlet located at the bottom (with respect to gravity), into a manifold and up into the microchannels. The level of liquid in the manifolds was controlled by use of a manometer. The fluid was then drained by gravity and a N₂ purge cleared remaining liquid from the microchannels. The nitrogen purge rate exceeded 140 SLPM for the device with 48 process and 48 fuel microchannels. If the distribution were uniform, which it is likely not, the per microchannel flowrate would exceed 2.9 SLPM during the nitrogen purge step. In this example, the thermally grown alumina layer was first treated with a La-containing solution, then an alumina sol (15 wt % alumina), then La-containing solution, and finally a Pt-containing solution (10 wt % solution). The device was then cut into pieces for analysis. The coatings exhibited excellent adhesion with no flaking. Elemental analyses were conducted at 100×, 500× and 2000× magnifications using energy dispersive spectroscopy (EDS) at 20 kV excitation energy. Unless specified otherwise, this is the condition (at 100×, or if 100× is larger than the area available, then the largest available area for SEM) that should be used for elemental analysis of any coatings described herein (recognizing that some modifications may be required if such