L.8: Deposition of thick SiC clad layer on Zircaloy-4 tube using laser additive manufacturing process

Zircaloy-4 (Zry-4) is being used as clad material for nuclear fuel in thermal nuclear reactors (PWR and PHWR) owing to its intrinsic properties such as low neutron absorption cross-section, high thermal conductivity with adequate creep and mechanical properties. However, high-temperature oxidation and hydrogenation of fuel cladding are still challenging issues. After Fukushima accident in year 2011, development of accident-tolerant fuel clad materials is initiated worldwide to improve the safety of nuclear reactor. Among various coating material, the coating of SiC on Zry-4 is found to be very promising for protecting the clad tube against oxidation and hydriding problem. Conventionally, SiC coating is deposited using techniques such as physical/chemical vapor deposition and magnetron-based techniques but thickness is limited to 20 µm due to delamination of coating. Hence, there is a need to develop a suitable technique to deposit thick coating of SiC (>100 µm) on long Zry-4 tubes.

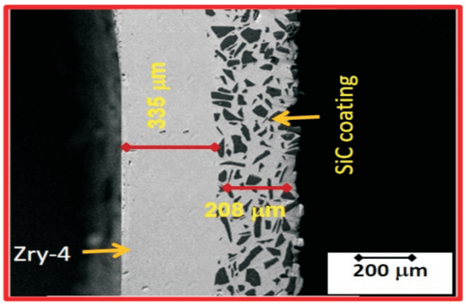

Fig. L.8.1: SEM micrograph across the cross-section of SiC coated layer and substrate.

Laser additive manufacturing based directed energy deposition (LAM-DED) is undertaken to develop thick SiC coating of ~200 µm on thin wall tube of Zry-4 alloy with thickness of 400 µm. Various laser-processing parameters such as laser power density, scan speed, powder feed rate and percentage overlap are optimized for deposition of SiC coating on Zry-4 tube to achieve uniform and homogenous coating layers. The initial deposition trials showed that the lower thickness (~400 µm) of Zry-4 tubes pose major challenge as it yields excessive dilution, thermal damage or complete melting of tube. To control this, a novel scheme of feeding Ar gas from inside diameter of the tube is attempted and it showed a promising trend. After the optimization of Ar gas flow at 20 lpm from inside diameter of the tube along with other laser processing parameters, the excessive dilution and thermal damage/ burning is controlled and defect-free deposition of SiC on Zry-4 tube was achieved. Figure L.8.1 presents SEM micrograph of SiC deposition obtained with Ar gas flowing from inside. It can be seen that the dilution of Zry-4 tube is reduced to a large extent with intact tube thickness around 335 µm and defect free deposit of SiC of thickness 208 µm is achieved. The optimized parameters yielding defect free SiC cladding are: laser power density of 4.52 kW/cm^2, powder feed rate of 2.71 gm/min. and scan speed 325 mm/min.

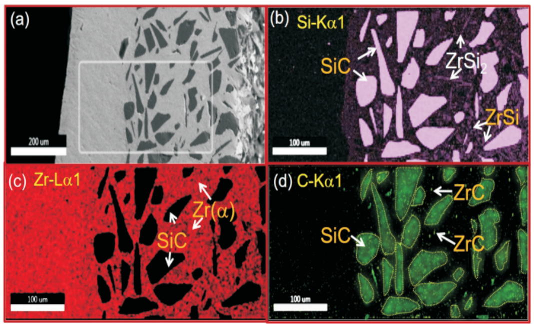

Fig. L.8.2: Areal EDS mapping of Si, Zr and C elements recorded across the cross-section of SiC coating on Zry-4 showing the presence of different phases.

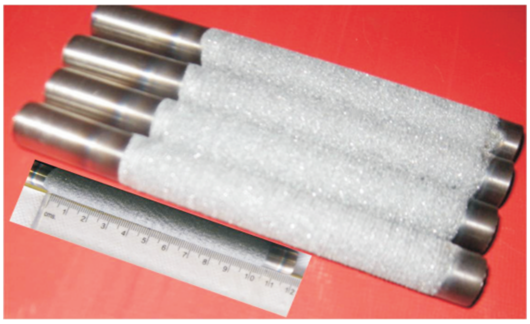

Fig. L.8.3: Photographs of Zry-4 coated with SiC over length of 100 mm.

Further, the interface between SiC clad layer and substrate (Zry-4) is characterized using energy dispersive x-ray spectroscopy (EDS) attached with SEM and x-ray diffraction to assess the homogeneity, uniformity, defects and to identify different phases formed across the interface. Figure L.8.2 (a-d) present the EDS map of major elements Zr, Si, and C, respectively. From XRD and EDS map, it is confirmed that the clad layer consists of Zr(α), SiC, $ZrSi_2$, ZrSi and ZrC type of phases. Formation of these phases may be due to intermixing of Zr-4 matrix and SiC during LAM-DED. It is reported that the solid solubility of Si and C elements in Zr matrix is negligible and there is higher probability of formation of Zr_2Si and ZrC. SiC clad layers were deposited on 10 mm diameter x 0.4 mm thick x 100 mm length of Zry-4 tube as shown in Figure L.8.3 and six numbers of coated tubes were sent to Reactor Engineering Division, BARC for further qualification.

Reported by:
C. P. Paul (paulcp@rrcat.gov.in)