Experimental Investigations of Laser Beam Welded and Post-Weld Heat Treated Nb-1%Zr-0.1%C Alloy and Process Innovation Aided by Artificial Intelligence to Make Welding Economical

Abstract

Laser beam welding (LBW) being a high energy density joining technique is preferred for welding both ferrous, non-ferrous and polymers of different thicknesses having applications in the automotive, nuclear, aerospace and chemical industries. Nb-1%Zr-0.1%C (PWC-11) is a solution-strengthened and precipitate-hardened alloy having the potential of structural material to be used in compact high-temperature reactors (CHTR). This alloy is the proposed structural material for the coolant channels to carry heat for hydrogen production. The utility and dependency of autogenous laser beam welded Nb-1%Zr-0.1%C are fundamental research objectives within the CHTR context. Laser beam welding of Nb-1%Zr-0.1%C was carried out in butt configuration to correlate the effect of energy density, viz, laser power, welding speed and laser beam diameter on the mechanical and metallurgical properties of the joint. The performance of the LBW alloy was assessed by carrying out a corrosion test in lead-bismuth eutectic (LBE) maintained at 1100 °C. The corrosion rate/dissolution behaviour of base metal (BM), fusion zone (FZ) and heat-affected zone (HAZ) were compared based on the weight and dimension change to address the possible reasons for material loss during the operation of carrying out molten LBE at 1100 °C. The increase in micro-hardness of FZ, HAZ and BM could be attributed to the increase in the fraction of low angle grain boundary (LAGB), formation of β-Zr (bcc) phase and oxides of niobium and zirconium. The increase in hardness is an indicator of oxidation, the reason underlying weight loss. β-Zr phase formation increases the susceptibility towards oxidation. The nitride and carbide phases of niobium and zirconium, and compressive residual stress improve the resistance of the alloy towards corrosion and oxidation. The corrosion rates of HAZ, FZ and BM were observed to be equal to 0.25, 0.12, and 0.07 mm/year, respectively. The weight loss %/yr in the BM, FZ and HAZ were seen to equal 0.71%, 1.33% and 2.70%, respectively. The corrosion susceptibility of HAZ was found to be the highest, followed by FZ and BM. Furthermore, the effects of thermal ageing time and temperature used during heat treatment were studied on the tensile strength, elongation, and microhardness of the LBW alloy. The segregation of zirconium, carbon and oxygen increased grain boundary energy and induced brittleness to the grain boundary, resulting in loss of ductility. For the post-weld heat treated (PWHT) samples, the plasticity was found to decrease to about 57% of that of the BM. This was attributed to the precipitation of carbides, grain growth, and dislocation pinning during the ageing process. During the heat treatment of the welded samples, both Yield Strength (YS) and Ultimate Tensile Strength (UTS) were found to decrease to 77% and 86%, of that of the BM, respectively. It had been found that PWHT is a highly resource-intensive material processing technique, resulting in a higher product price for the end customer. Moreover, reactive metals, such as niobium, titanium, and tantalum necessitate particular heat treatment arrangements, further complicating the heat treatment procedure. Post-weld heat treatment of thin sheets of metal (such as niobium in this study) is also difficult due to distortion. To address these challenges, an attempt was made to use artificial intelligence (nature-inspired meta-heuristic optimization technique) to reduce the post-weld treatment procedure. Bonobo Optimization algorithm, which could arrive at the globally optimal solution in fewer iterations than particle swarm optimization (PSO), had the fastest rate of convergence. The mechanical properties of the experiment carried out using optimized parameters, i.e., yield strength (YS), ultimate tensile strength (UTS) and elongation (El) were found to decrease to 85.94%, 98.48% and 58.65%, respectively, of that of the BM and exceeded the PWHT results by 10.13%, 12.51% and 2.75%. Therefore, an AI-based intelligent nature-inspired optimization tool is able to guide the researchers to select the set of input parameters, so that the enhanced mechanical properties of the weld could be achieved even without carrying out the costly PWHT.

Keywords: Laser beam welding; Refractory alloy; Nb-1%Zr-0.1%C; Compact high-temperature reactors; Oxidation; Corrosion; Post-weld heat treatment; Recrystallisation; Artificial intelligence; Bonobo optimizer; Particle swarm optimizer