ABSTRACT

Nickel-based superalloys such as Inconel alloys 718, 706, 625, and 945 are employed mostly in components of aviation engines, gas turbines, oil and gas, and other industries. Despite their superior weldability, fusion welded Inconel 718 joints suffer from metallurgical issues such as secondary phase formation, HAZ liquidation cracking, etc. when subjected to higher heat input during traditional welding methods. A novel Spin Arc Gas metal arc welding produces better weld quality due to its low heat input conditions. Inconel superalloy components can also be fabricated directly by controlling the heat input by one of the direct energy deposition additive manufacturing methods called wire arc additive manufacturing (WAAM).

The mechanical and metallurgical characteristics of Gas Metal Arc (GMA), Gas Tungsten Arc (GTA), spin arc GMA welded Inconel 718 and Incoloy 945 alloy joints were less explored. Though different post weld heat treatments of Inconel alloys were investigated the mechanical and metallurgical characteristics of GMA and GTA and spin arc GMA welded and heat-treated Inconel 718 and Incoloy 945 alloys joints were not carried out widely.

In the present fully sponsored research work, the weldability studies of Inconel 718 and Incoloy 945 were performed using Spot Varestraint and circular weldability tests. GMAW, GTAW and Spin arc GMAW of Inconel 718 and Incoloy 945 were carried out. The welded discs were heat treated using solution annealing, single- and double-step aging heat treatments. The welded, as well as the heat-treated Inconel super alloys, were characterized to obtain their metallurgical and mechanical properties. Inconel 625 alloy was mainly used in oil and gas industries for valve components in order to improve its properties. There were no such works on WAAM process using robotic welding of Inconel 625 alloy. For the study purpose, an Inconel 625 slab of

size 300 mm x 150 mm x 15 mm was fabricated using WAAM process and its mechanical and metallurgical properties were investigated.

Weldability of the Solution Annealed (SA) and aged Inconel 718 and Incoloy 945 were determined using Spot Varestraint test from the measured number of cracks in the weld metal (WM) and HAZ region. It was found that both alloys had good weldability. Also, in the modified circular patch weldability tests of Inconel 718 performed to investigate liquation cracking in the HAZ, no cracks were found. From the metallurgical and mechanical characterisation of the discs used for the weldability studies, the average volume fraction of laves and Nb carbides contained in the WM was found to be 16 ± 1.5 % and 21 ± 2 % respectively. Also, the average microhardness of the base metal (BM), HAZ, and WM were 382 ± 2 HV, 387 ± 4 HV, and 348 ± 5 HV respectively.

Initially, bead-on-plate welding trial runs were carried out on Inconel 718 plates using L9 orthogonal array to determine the desired GMAW process parameters based on the heat input. Using the selected process parameters four sets of semi-circular discs of Inconel 718 and 945 alloys of dia. 250 mm and 13 mm thickness having Double-V joint configuration were joined using Inconel 718 (ERNiFeCr2) and Incoloy 945X fillers. The welded discs were heat treated using annealing, single- and double-step aging processes. After the post-weld heat treatment (PWHT), the metallurgical and mechanical properties of three Inconel 718 and one Incoloy 945 GMA welded joints were studied. The WM had a columnar dendritic structure and the laves and Nb carbide particles were uniformly spread in both the heat-treated alloys. The grains and the average volume fraction measured using Metal plus software of the laves and NbC present in the WM of Incoloy 945 alloy were less compared to that of Inconel 718 alloy. The Tensile strength and microhardness of the WM of Inconel 718 in double aged condition were higher than that of its BM. The WM of Incoloy 945 alloy had higher hardness

(340 ± 5 HV) and lower ultimate tensile strength (UTS) (1117 ± 3.5 MPa) when compared to its BM (280 ± 5 and 1179 ± 2 MPa).

After the selection of GTAW process parameters based on the heat input condition, semi-circular disc of Inconel 718 alloy of dia. 250 mm and 13 mm thickness was joined. The welded disc was heat treated using a double-step aging process. The metallurgical and mechanical properties of the PWH treated Inconel 718 welded joint was investigated. The SEM microstructures of WM feature a fine dendritic structure with a few laves phases and NbC in the NiCr-matrix, as well as NbC in the WM, as revealed by a TEM micrograph. The average volume fraction of laves and NbC in the WM of PWH treated 718 alloy was 15 ± 2% and 41 ± 5 % respectively. The WM had higher hardness and UTS than that of the BM and HAZ.

The experimental welding trails were accomplished using three levels and three factors Box-Behnken Design matrix to develop regression models to predict the weld bead parameters such as Bead Width (BW), Bead Height (BH), and Depth of Penetration (DP) of spin arc GMA welded Inconel 718 plates. The adequacy of the developed models was tested using Analysis of variance (ANOVA), adjusted R^2, tabulated F-ratio, and the conformity test. The cause and effects of the spin arc GMAW process parameters on weld bead geometry were analysed using the regression models.

The optimum spin arc GMAW process parameters to have maximum BH, DP, and minimum BW were determined using the multi-objective optimization approach available in the Design Expert software. The optimal spin arc GMAW process parameters were found to be: spin speed = 2516 rpm, spin diameter = 2 mm, and welding speed = 31 cm/min, with a desirability of 0.908. From the conformity test conducted to validate the optimum bead geometry, the error percentage of BW and BH models was found to be less than 1 % and the DP model had less than 7%.

Multipass welding was performed to join 13 mm thick Inconel 718 discs using optimal spin arc GMAW process parameters. The microstructural and mechanical characterisation of the spin arc welded 718 alloy in the as-welded condition was performed. The evaluated average volume fraction of laves and NbC in the WM were 10.5 ± 1.5 % and 18 ± 2.55 % respectively. The WM microstructure exhibited fine columnar dendritic structure. The grain size and the volume fractions of laves and NbC present in the WM are less when compared to that of all the heat-treated GMA and GTA weld metals. The average UTS was found to be 1095 ± 1.5 MPa which was 91 % of its base metal's strength. The microhardness hardness of the WM was relatively higher than that of its BM.

A rectangular Inconel 625 alloy slab of size 300 mm x 150 mm x 15 mm was fabricated using Robotic GMAW WAAM process. One-half of the fabricated slab was solution annealed and the mechanical and metallurgical characterisation of both half slabs were carried out. A columnar dendrite structure containing laves phases, NbC and MC carbides was present in WM and the intermetallic phases were dissolved in the matrix of SA deposit. The presence of secondary carbides $M_{23}C_6$ and M_6C was also observed in both the WM microstructures. The average volume fraction of laves phases present in the as-deposited and SA alloys was 18 ± 5 % and 5 ± 1.5 % respectively. Electron probe microanalysis revealed 3.8 ± 1.5 vol.%. of intermetallic phases in the SA alloy, which was lesser than that present in the as-deposited alloy. In the as-deposited alloy, TEM micrographs indicated the existence of uneven NbC. When compared to SA alloy, it was observed that the as-deposited alloy had higher tensile strength and microhardness.