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Utilization of the modified Taguchi method in CFD simulations for optimal laser beam welding parameters of Zr-Nb alloy for nuclear and chemical industrial applications

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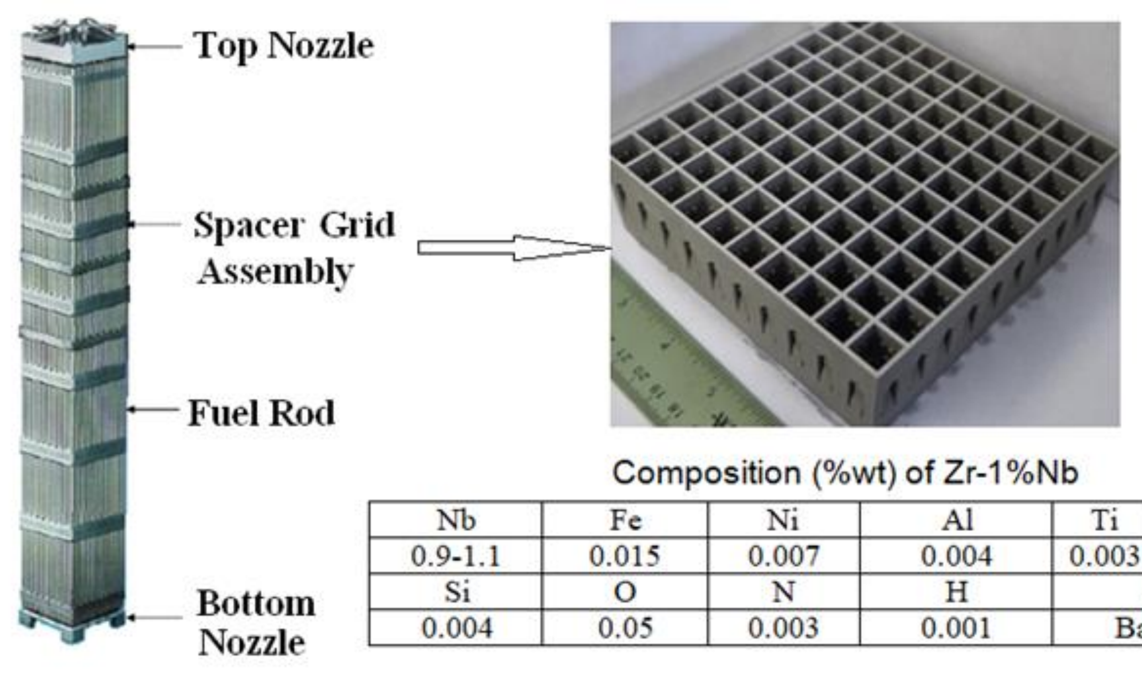
Abstract: This presentation deals with validation of numerical simulations with test results of different materials and welding processes. Modified Taguchi's design of experiments and analysis of variance (ANOVA) are utilized to assess the contribution of process parameters on output responses simulating numerically with few test runs on Zr-Nb alloy. It also highlights on the development of empirical relations for generation of weld bead profiles.

Introduction: Laser welding has been widely used in a variety of industrial applications for joining of materials at high power intensity with low thermal distortion and low metallurgical damage. Nuclear and chemical industries are focused on Zr-Nb alloy due to its strength and corrosion resistance. Selection of optimal welding parameters plays a major role in achieving quality weld by acquiring essential knowledge of temperature and velocity fields during process in FZ (fusion zone) and HAZ (heat affected zone). The expensive trial and error methods for weld bead profiles in terms of the laser welding process parameters demand several numerical and experimental simulations. Such methods sometimes may not yield fruitful results. A simple and reliable multi-objective optimization approach is followed here in the modified Taguchi approach to trace optimal laser beam weld (LBW) parameters for weld bead profiles.



Composition (%wt) of Zr-1%Nb

Nb	Fe	Ni	Al	Ti	C
0.9-1.1	0.015	0.007	0.004	0.003	0.02
Si	O	N	H	Zr	
0.004	0.05	0.003	0.001	Balance	

Figure-1: PWR fuel rod assembly

Multi-Objective Optimization

Adopting the Taguchi's L_9 orthogonal array and the multi-objective optimization the laser welding process parameters are identified to achieve maximum depth of weld and minimum width of the fusion zone of zirconium alloy E110.

Assignment levels of laser weld process parameters

Control Factors (Input parameters)	Designated Factor	Level – 1	Level-2	Level-3
Welding speed (mm/s)	A	6	8	10
Power (W)	B	200	300	350
Laser beam diameter (mm)	C	0.5	1.0	1.5

Fusion zone and Optimum input parameters	Approach	Depth of weld, α (mm)	Width of Fusion zone, β (mm)	Size of HAZ, γ (mm)	Maximum temperature δ (K)
 Optimum Depth and Width $A_2B_3C_1$	Numerical results	2.990	2.476	1.351	4713
	Taguchi	2.9495	2.3558	1.2032	4583
	Expected range	2.73 – 3.12	2.27 - 2.47	1.07 - 1.37	4313 - 4723

Concluding Remarks

- A coupled thermo-fluid structural model is developed and validated with test data of weld bead geometries.
- Provided the temperature and velocity fields, weld thermal cycle, weld pool geometry and solidification parameters of Zr-1%Nb.
- The spatial feature of temperature in the weld zones will be helpful while studying the microstructure in fusion and HAZ.
- Taguchi approach combined with multi-objective optimization will be useful in developing the empirical relations for the weld bead geometries in terms of laser welding process parameters by performing few experiments or numerical simulations. They also provide optimum welding parameters to achieve the required quality weld.
- Thermo-fluid flow analysis can be extended to the complicated welding process of nuclear fuel rod components.

Materials & Methods : A three-dimensional non-linear thermo-fluid model is developed for LBW incorporating buoyancy and Marnangoni stress using ANSYS Fluent and embodied with VC++ code. The spacer grid is one of the core and critical component of fuel rod assembly process. Figure-1 shows a fuel rod assembly of a pressurized water reactor (PWR) consisting of fuel rods, top nozzle, bottom nozzle, guide tubes, spacer grids and instrumentation tube. The spacer grid material is zirconium alloy E110 (Zr-1%Nb).

Experimental Validation

Tests are carried out on E110 alloy sheets ($110 \times 10 \times 0.5\,mm$) using LTA-4A-2 Nd:YAG laser welding machine at Polyus Scientific and Production Center JSC, Tomsk, Russia. The technical characteristics of the laser welding machine are: 1.064 µm wave length; 100 mm focal length; 0.2 to 2 mm focal spot diameter; 1 to 150 Hz pulse frequency; 2 to 20 ms pulse duration; and to a maximum of 50 J pulse energy. Argon 99.993% purity is used at the rate of 60 l/min on both sides. The beam diameter is 0.95 mm. Figure-2 shows a butt joint having full depth of penetration for the frequency of 5 Hz, pulse duration of 14 ms, welding speed 1.12 mm/s and peak power of 780W. Figure-3 shows simulated weld-pool cross-section and HAZ. The fusion zone (FZ) width at the top surface is measured as 1.37 mm, whereas it is 1.40 mm from numerical simulations. The heat affected zone (HAZ) is measured as 3.28 mm, whereas it is 3.37 mm from numerical simulations. Test results are matching well with measured data.

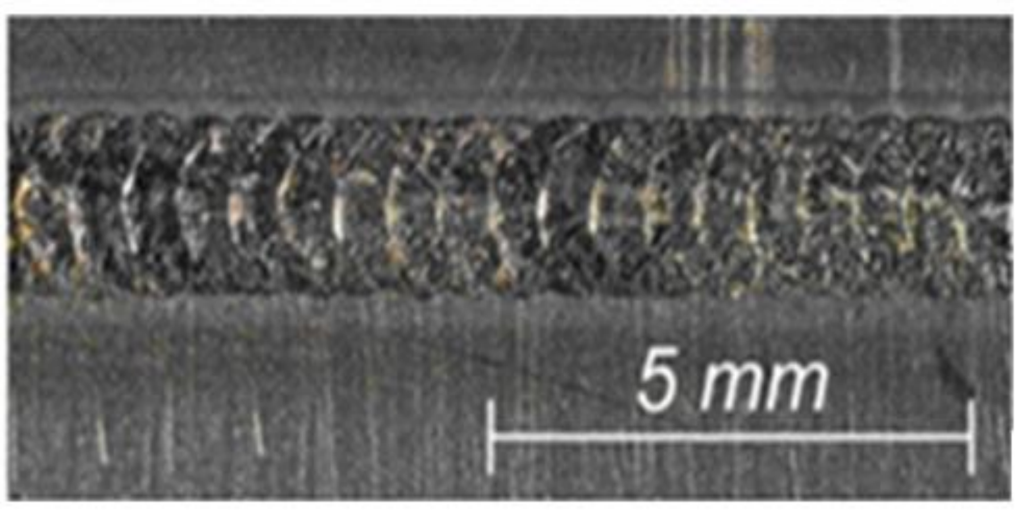


Figure-2: Butt-weld joint having full depth of penetration

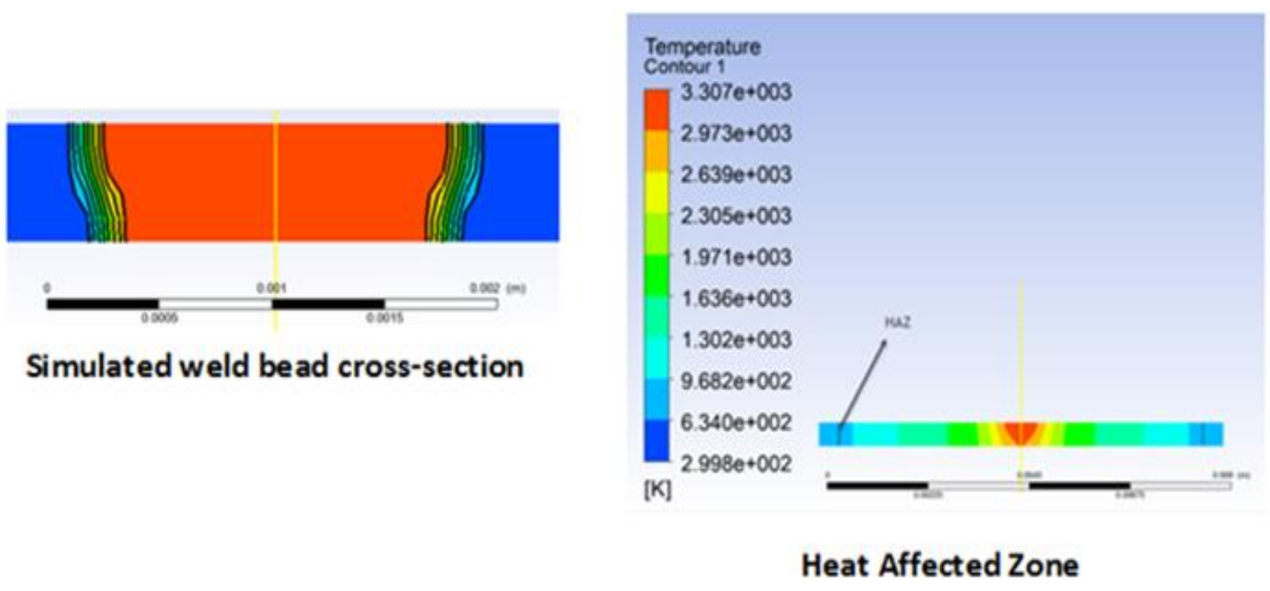


Figure-3: Simulated weld pool cross-section and HAZ

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