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Welding Distortion Assessment for Hydraulic Connections of Complex Assembly of Neutral Beam Accelerator Grid

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Abstract

Negative Ion Neutral Beam (NB) accelerator grids, made up of Oxygen free copper are actively cooled and are connected to external hydraulic circuit by welded connection. Cooling pipes are of SS316L material and Grids are manufactured with the oxygen free material (CuOF), which are welded with the transition stubs provided of Inconel material. Grids have the very high tolerances (in the range of microns) in terms angles, flatness and positional accuracy of the features. The welding of cooling pipe assembly to the grid plate introduce distortion which can affect the achieved tolerances on the main functional area of the machined grids.

Considering the requirement of angles, flatness and the positional tolerances of gird plate and its features; the need arises to have the assessment of weld induced distortion on functional area of CuOF Plate. Additionally, it is also necessary to assess the direction of the stress propagation, considering the dissimilar weld and having the mass difference in the plate and pipe assembly. Various configurations have been assessed and the welding simulation was performed to study the distortion on the assembly.

Key words: Welding Simulation; SYSWELD; Distortion; Optimization.

1.0 Introduction

Welding distortion is one of the major concerns of the industrial joining practice [1]. During welding, the base metal is heated and expands in a non-uniform manner and upon cooling, itresults in shrinkage stresses between base metal and weld metal. The expansion and contraction which occur during the heating and cooling cycle of the welding process result in the 'Distortion' of the weldment [2]. Control of such distortions is of paramount importance to ensure the desired manufacturing tolerances and the least residual stresses within the welded components. Conventionally, distortion control can be achieved through repeated trials, which results in achieving the optimal welding conditions. However, for the present study, a preliminary route to finalizing the welding conditions is through numerical simulation which enables a virtual examination of the welding distortion without performing expensive experiments. Heat transfer mathematical models [3-4] are being developed and optimized for simulating the different fusion welding processes, and validated with the experimental results. Weld modeling enables thorough assessment of distortion with the different welding parameters and welding and clamping sequences in the pre-development stage [5]. Considering the huge experimental and examination cost for analyzing the weld behaviour, numerical simulation of weld induced distortion becomes a crucial part of the welding research and development. Several researchers; Tekriwal et al. [6], Deng et al. [7], Brown et al. [8] worked on the welding distortion assessment and their effect on the overall structural assembly and performance.

The paper presents the weld distortion results of the cooling pipe assembly welding with the accelerator grid plate [9] and the effect of weld distortion on the accelerator grid plate tolerances. Welding plan and the clamping conditions have also been optimized to the control the induced distortion. The simulation also established the need and type of the flexible element to be incorporated into the pipe assembly to accommodate the distortion induced by the assembly welding.

2.0 Welding Simulation

The WELD PLANNER module of SYSWELD software was utilised to simulate welding distortion of the SS316L hydraulic pipes to the oxygen free copper plate. The software WELD PLANNER is dedicated to identify distortions, critical weld joints, clamping conditions and weld sequences using the shrinkage volume method.The shrinkage volume approach is the fastest and least complex method for the prediction of the welding distortion. The shrinkage approach assumes that the linear thermal contraction is responsible for the distortion; the elements shrink with a value that is equal and opposite to the thermal expansion, when the material is heated up to its melting temperature during welding. In this simulation, shrinkage-based assessment has been performed. For this approach, the effect of the weld is approximated by imposing shrinkage of the material in the weld bead.

Fig. 1 shows the CAD model of the oxygen free copper grid with the hydraulic circuit to be welded on both the sides. Inconel insert plate is used between the oxygen free copper and SS316L for the dissimilar weld transition. Thickness of the grid plate is 8 mm and the pipe diameter is of 25 mm with a wall thickness of 1 mm. To simulate the welding of grid with hydraulic lines assembly, only half model (with symmetric boundary conditions) has been considered as the welds on one side of the copper grid are same and do not influence the deformation on the other side.

Two different configurationshave been considered for the weld distortion assessment, **Fig. 2a** shows the baseline design of the hydraulic pipes welded with the copper grid through an Inconel transition and **Fig. 2b** shown the modified design with the 'U' bends, with the assumption that it would provide some flexibility and help in absorbing the distortion caused by the welding stresses.

2.1. Meshing of the Model

During welding, only a small portion of any material undergoes an intense cycle of heating and cooling. This consists of the portion where the heat input is provided and the surrounding area known as Heat Affected Zone (HAZ). In order to get the accurate results, this portion has been fine meshed. For the application of the shrinkage based methodology, a shell-solid mixed mesh model of the assembly is used for the representation of the structure. Meshed model constitutes of

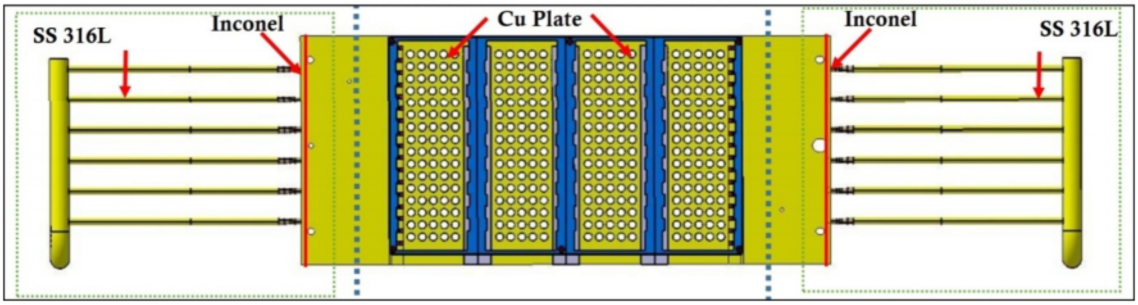

Fig. 1 : Beam Source Grid with the Hydraulic connections

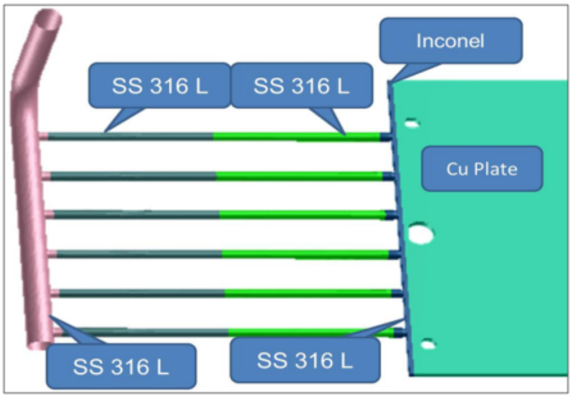

Fig. 2a : Baseline design of Hydraulic pipe welded with copper grid;

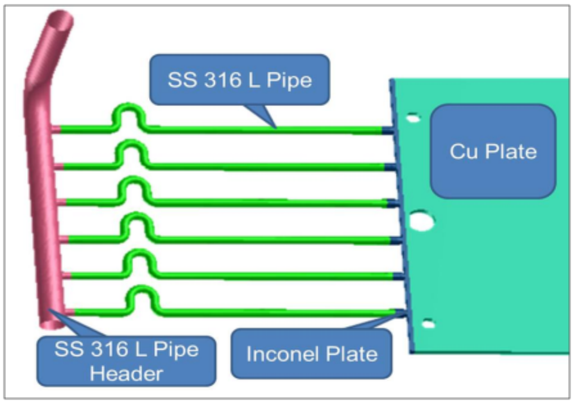

Fig. 2b : Modified design with U-Bend

tetrahedral solid and rectangular shell elements. The symmetric model in total has 243570 elements and 77899 nodes.

2.2. Material Properties

The material properties required for the shrinkage based distortion assessment using WELD PLANNER are Young's elastic modulus, Poisson's ratio and thermal expansion coefficient at room temperature. These are listed in **Table 1** for the three material under consideration in this study.

Table 1 : Material Properties [10]

Materials	Elastic Modulus (N/mm^2)	Poisson's Ratio	Thermal Expansion Co-efficient 1K	Melting Point
Copper	117000	0.33	0.00002	1050
Inconel 625	196000	0.31	0.000012	1300
SS316L	195000	0.30	0.0000199	1400

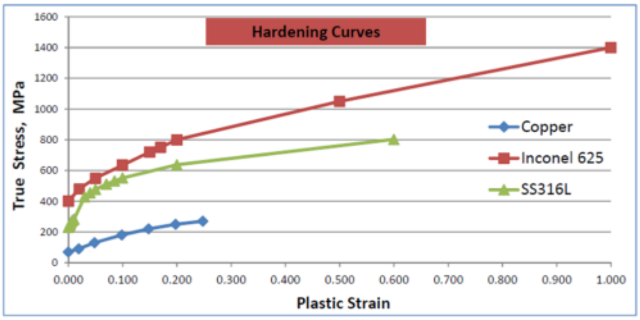

Fig. 3 : Straining Hardening curve for the materials

2.3 Assembly Sequence

The assembly strategy is designed to make use of the inherent properties of the geometry like general flexibility of the small diameter tubes, specific flexibility of the U-bends– ability to absorb the axial expansion/contraction and high stiffness of the grid. Each of the two configurations mentioned above require a clamping sequence to be followed during assembly in order to minimize the stored elastic energy during welding. Further in order to have the final welded assembly, two different assembly strategies have been considered for each configuration. The same are described below.

2.3.1. Configuration 1– Clamping Sequence

Five different clamp sets are used for different stages of the welding as shown in **Fig. 4**. Clamp set 1 and 2 are used for the stage 1 welding, which is copper grid to the Inconel transition plate, which have the machined cooling pipe stubs. Pipe stubs are clamped on the ends and the copper plate is held at two locations. Clamp set 3 is used for the stage 2 welding; i.e. welding of small tubes (SS316L) to the Inconel ended stubs. Clamp set 4 is used for welding the small tubes (SS316L) to the already welded tubes (SS316L) on the Cu grid end and clamp set 5 is used welding the small tubes (SS316L) to hydraulic header (SS16L), in this header is clamped on the open end sides. Weld Nos (W1 – W19) are also defined for each stage of welding, shown in **Fig. 4**.

Assembly Strategy 1 (See **Fig. 5a**): (A) Cu plate to Inconel plate; (B) A + first section of each cooling pipe; (C) B + second section of each cooling pipe; (D) C+ cooling header.

Assembly Strategy 2 (See **Fig. 5b**): (A) Cu plate to Inconel plate; (B) A + first section of first cooling pipe; (C) B + second section of first cooling pipe; (D) C+ header; (E) repeat for second tube etc.

2.3.2. Configuration 2– Clamping Sequence

Five different clamp sets are used for the three stage welding of the grid to pipe assembly as shown in **Fig. 6**. As similar to configuration 1, clamp set 1 and 2 are used for the stage 1 welding. In the stage 2 welding, i.e. welding of small tubes with the end plate; clamp set 3 and 4 are used to clamp at pipe end and to support the pipe at the mid of its length during welding. Clamp set 5 is used during welding of pipe and gird assembly with the main header. Header is clamped at two of its open ends. Weld Nos (W1 – W13) are also defined for each stage of welding, as shown in **Fig.6**.

Assembly strategy 1: (A) Cu plate to Inconel plate;
(B) A + cooling pipe; (C) B + header pipe.

Assembly strategy 2: (A) Cu plate to Inconel plate;
(B) A + cooling Pipe + header pipe

2.3.3. Welding Sequence

Welding sequence for each of the assembly strategy for both the configurations play an important role to control the overall distortion. In order to determine the combination of weld sequence and clamping conditions which result in minimal distortion on the assembly, a series of different configurations have been assessed. **Table 2** and **Table 3** shows the welding sequences considered for both the configurations with different assembly strategy.

In table 2, first column refers to the welding sequence (WS) (01 – 07) and last column defines the assembly strategy (AS) considered for each welding sequence. Considering the WS 01 and AS 1, all the welds (weld no. W1 to W19) were carried out in the sequence mentioned in 2nd row of the **table2**. Similarly, the other rows define the weld sequence followed for weld no W1 – W19. Similar methodology has been adopted for the each welding sequence and assembly strategy of configuration 2.

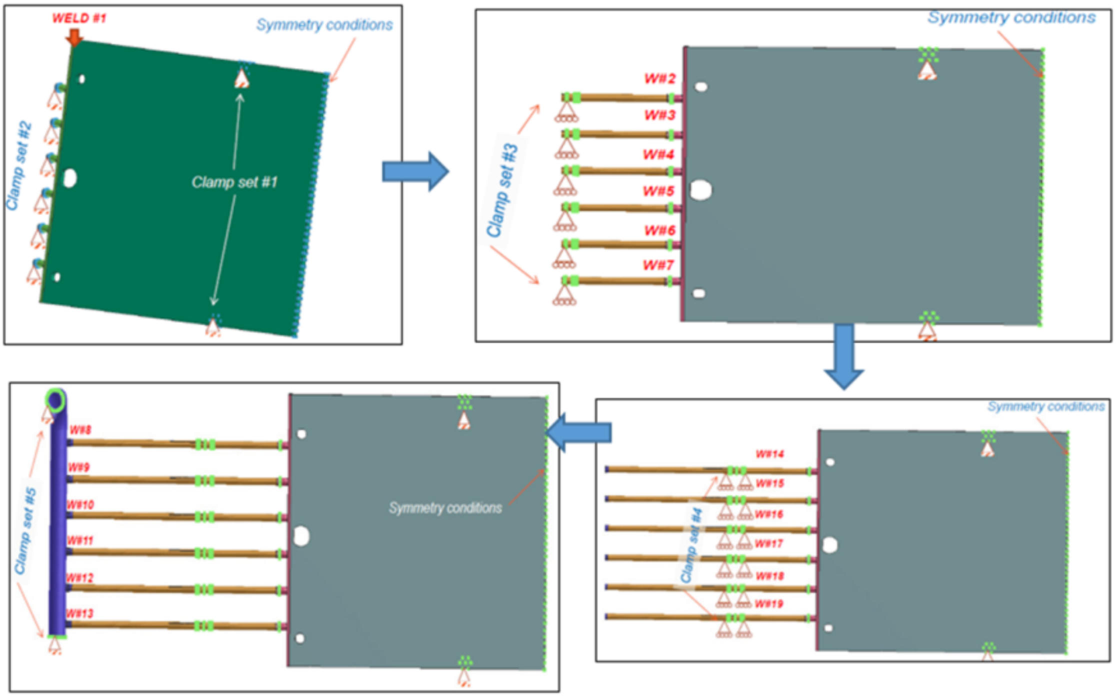

Fig. 4 : Clamping details with welding sequence for configuration 1

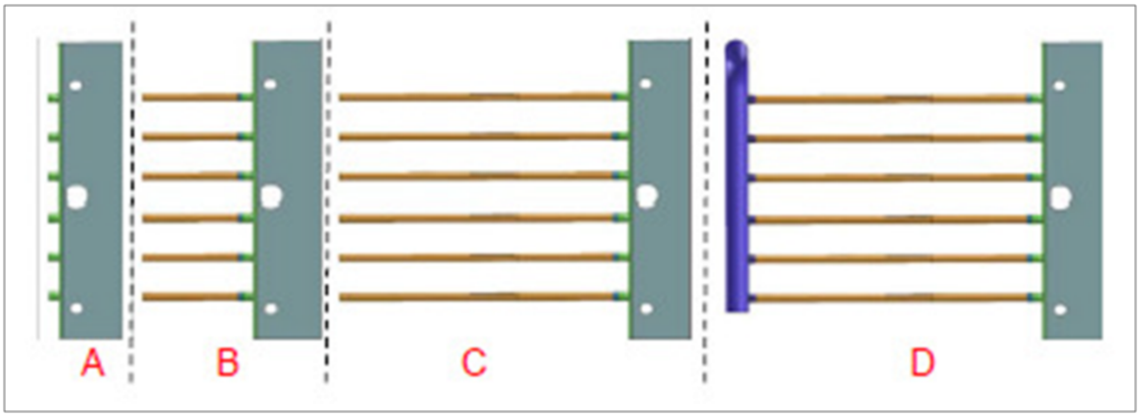

Fig. 5a : Assembly Strategy 1

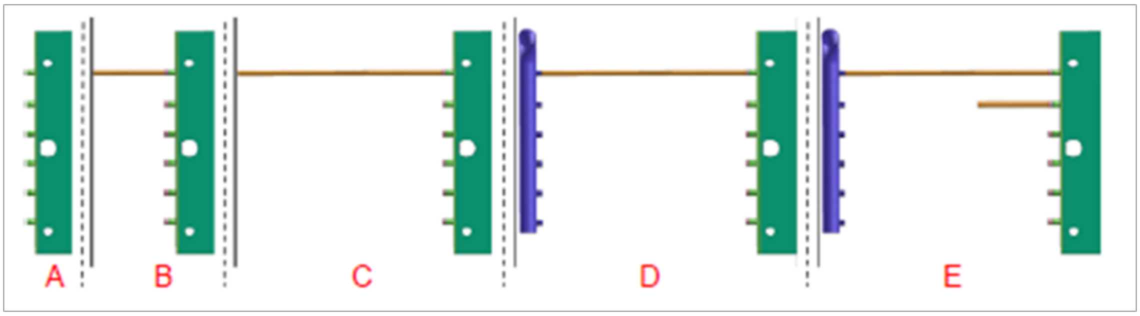

Fig. 5b : Assembly strategy 2

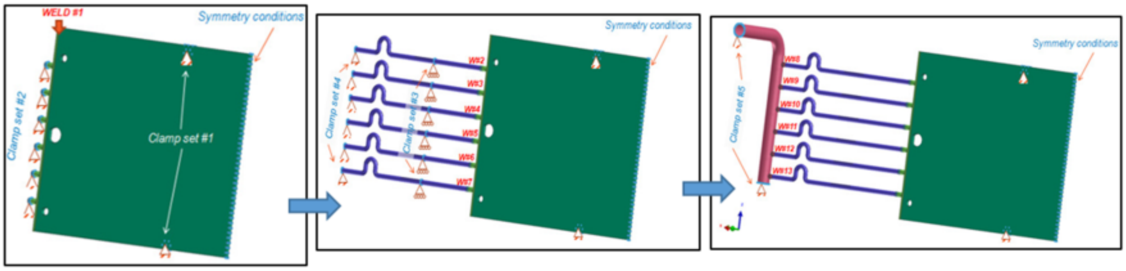

Fig. 6 : Clamping details with welding sequence for configuration 2

Table 2 : Welding Sequence for Configuration 1

WS	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	12	AS
01	W1	W2	W3	W4	W5	W6	W7	W14	W15	W16	W16	W18	W19	W8	W9	W10	W11	W12	W13	1
02	W1	W2	W3	W4	W5	W6	W7	W19	W18	W17	W16	W15	W14	W8	W9	W10	W11	W12	W13	1
03	W1	W2	W3	W4	W5	W6	W7	W19	W18	W17	W16	W15	W14	W12	W12	W11	W10	W9	W8	1
04	W1	W2	W3	W4	W5	W6	W7	W14	W15	W16	W17	W18	W19	W8	W13	W9	W12	W10	W11	1
05	W1	W2	W14	W8	W3	W15	W9	W4	W16	W10	W5	W17	W11	W6	W18	W12	W7	W19	W13	2
06	W1	W2	W14	W8	W7	W19	W13	W3	W15	W9	W6	W18	W12	W4	W16	W10	W5	W17	W11	2
07	W1	W4	W16	W10	W5	W17	W11	W3	W15	W9	W6	W18	W12	W2	W14	W8	W7	W19	W13	2

WS : Welding Sequence, AS : Assembly Strategy

Table 3 : Welding Sequence for Configuration 2

WS	1	2	3	4	5	6	7	8	9	10	11	12	13	AS
01	W1	W2	W3	W4	W5	W6	W7	W8	W9	W10	W11	W12	W13	1
02	W1	W2	W3	W4	W5	W6	W7	W13	W12	W11	W10	W9	W8	1
03	W1	W2	W7	W3	W6	W4	W5	W8	W13	W9	W12	W10	W11	1
04	W1	W2	W7	W3	W6	W4	W5	W13	W8	W12	W9	W11	W10	1
05	W1	W2	W8	W7	W13	W3	W9	W6	W12	W4	W10	W5	W11	2
06	W1	W2	W8	W3	W9	W4	W10	W5	W11	W6	W12	W7	W13	2
07	W1	W8	W2	W9	W3	W10	W4	W11	W5	W12	W6	W13	W7	2

WS : Welding Sequence, AS : Assembly Strategy

3.0 Results and Discussion

Welding simulation was done based on the welding sequences and clamping condition defined in table 2 and table 3 for configuration 1 and configuration 2 respectively. Table 4 shows the weld distortions obtained for different weld sequences for each of the weld configuration. As shown in **Fig. 7** for configuration 1, the minimum deformation of 0.375 mm is found for weld sequence 3 and the maximum deformation of 0.413 mm is found in weld sequence 5.

Table 4 : Welding distortion

Welding Sequence	Maximum Distortion (mm) Configuraton 1	Maximum Distortion (mm) Configuration 2
01	0.392	0.322
02	0.393	0.324
03	0.375	0.325
04	0.386	0.325
05	0.413	0.337
06	0.391	0.335
07	0.383	0.318

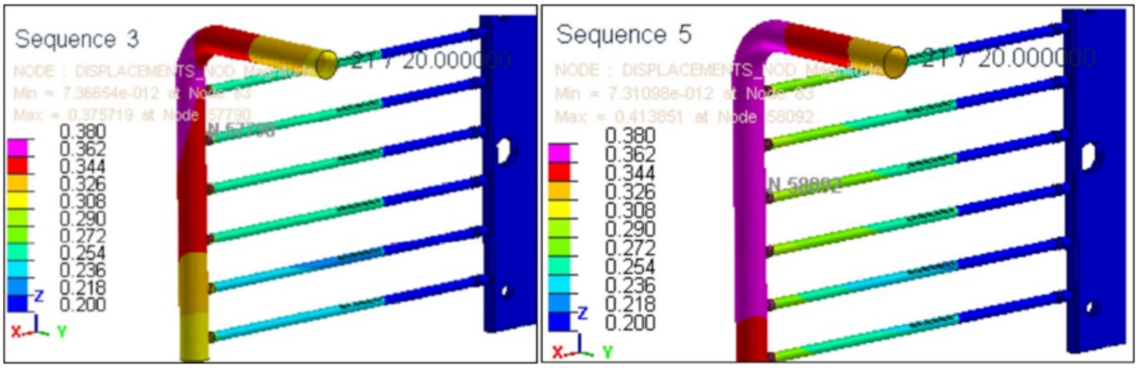

Fig. 7 : Welding distortion for welding sequence 3 and 5 for configuration 1

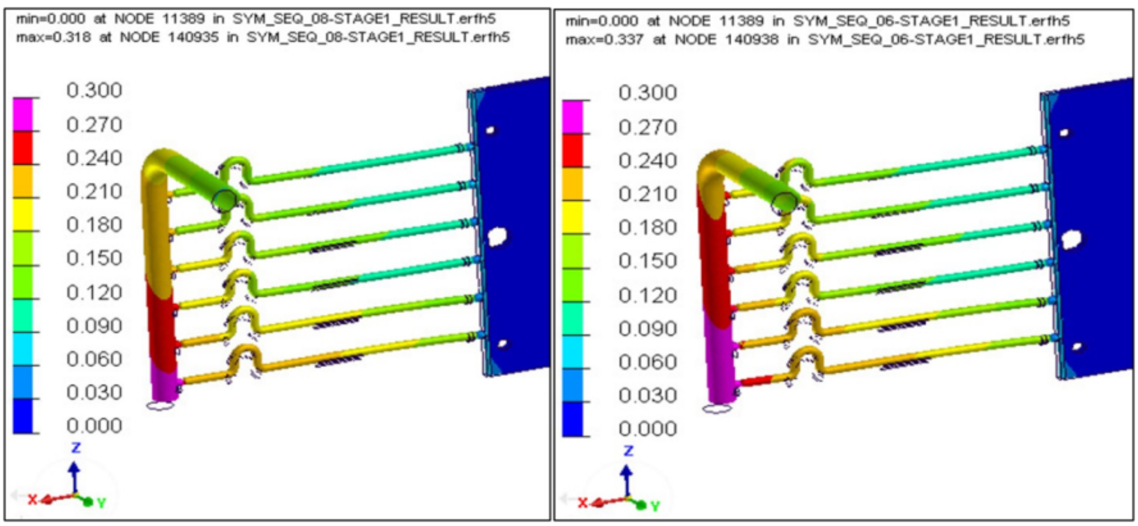

Fig. 8 : Welding distortion for welding sequence 7 and 5 for configuration 2

For configuration 2, the minimum deformation of 0.318 mm is found for weld sequence 7 and the maximum deformation of 0.337 mm is found in weld sequence 5 (See **Fig. 8**).

4.0 Conclusion

It is observed that the predicted distortion pattern for all the cases studied, are in the range of ~0.318mm to ~0.413mm in release conditions. It can be seen that configuration 02 produces the lower distortion in the unclamped condition as against configuration 01. The analysis result also shows that, with the optimized clamping conditions and the weld sequence, the weld distortion observed in the assembly welding of Cu to Inconel plate and with SS316 pipes & header does not propagate towards the main functional area (apertures) of the grid plate. This has provided the guidelines to be followed during the production welding to ensure that the already achieved functional tolerance of the machined grid remains unaffected. Additionally, welding distortion achieved through the simulation provide the inputs for the design of flexible element.

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