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Thermal Distortion Analysis by Inconel Over-Lay At Circular Moonpool Structures

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Abstract

This study is mainly interested in roundness of a circular moonpool structure in FPSO. Because this structure needs abrasion-resistance on inner wall, we should do buttering widely and deeply by using Inconel. But a general buttering can cause a severe distortion at structures. If someone can analyze the roundness by thermal distortion under Inconel over-lay, an erection policy can be established. In this study, shrinkage methodology by designed stress-strain curve was used and the result allowed deciding an appropriate block size.

Keywords: Shrinkage methodology, Moonpool, Inconel, Over-lay, Roundness deviation, Thermal distortion

1. Introduction

Among materials used in naval architectures, some should have high abrasion-resistance and corrosion-resistance to guarantee their working at special circumstances. They are good examples that there are inner flows or a friction expected by bearing-touch. Austenitic stainless steels and Inconel alloys containing nickel can meet those needs. Normally, the former could be used mainly for an economical reason as SUS316 etc. But the latter has abrasion-resistance and corrosion-resistance at even 600~900℃. Inconel alloys should be used inevitably in such a case.

One of the economical solutions is over-lay welding where Inconel alloys are needed. In order to make special effect on whole surface or to control level higher, over-lay weld will be done. It is slightly different from buttering that makes up for gap of butt. Though the over-lay heights will vary for their purpose, normal height is within 3 ~ 6 mm as economical reasons changing base metals.

By the way, over-lay is a kind of welding accompanying a thermal cycle, so that it can cause some problems in erection stages. Welding usually makes distortions by shrinkage of welded region under constraints of adjacent regions. For example, positions of bolt holes at pipe-flanges will be distorted (come close each other) by over-lay welding at inner wall. The larger a structure is, the more severe problem we can meet [1]. Among naval architectures having high portion of outfitting, the FPSO having a circular moonpool structure is controlled as 6mm-accuracy at its roundness of 20m-diameter. But, if over-lay welding is done at whole circular bearing-touch position by 1m-width, roundness control will be very hard work because of ship-block distortion by welding shrinkages.

This study aims to solve these kinds of problems, and an analysis using strain-boundary methodology based on elastic-plastic materials (Fig. 2) [2] (Ha, 2011) has been done at ship-blocks containing Inconel over-lay. This method is a kind of shrinkage methodology [3] and is known for economical tool for predicting thermal distortion. The results of this study can help not only reverse-fabrication at parts expecting distortions but also making a policy of manipulating cranes by erection block size. Furthermore,

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by comparing measured datum of welded structures to their analysis results, I will show that the strain-boundary method is reliable even at nonferrous welding materials.

2. Strain Boundary Condition Method Based on EP Materials

As for the methodology which can analyze thermal distortion very fast even at large shell structures like ship blocks, there are equivalent forces method [4] and strain-direct boundary condition method (SDB Method) (Fig. 1) [5]. The former is based on imaginary compressional forces & moments instituting welding shrinkage. In case of simple structures, basic formulae of beam theory can be directly used without commercial FEM code. It is general that imaginary forces are gained by integrating inherent strain [6]. In contrast; the latter induces shrinkages by instituting thermal expansion coefficient to inherent strain. Two methods are also different at making bending distortion induced from non-symmetric bead & HAZ section on the basis of neutral axis. The former makes bending by equivalent moment, but the latter uses layers within shell element. Even though there is one material, there are two layers (top & bottom) (Fig. 1). If the imaginary temperature at each layer as boundary condition is different from each other, shell element would describe bending deformation. This methodology does not need to decompose imaginary forces (vector input) by their axes because of scalar input (imaginary temperature) and to worry about rigid body motion. Furthermore, shrinkage of welded region by itself will make compressional stress field like real structures.

Strain (direct) boundary (SDB) method has been often used at large shell structures having curved welding lines based on elastic materials because of its very fast analysis time. But, it still has some difficulties in calculating inherent strains. In the process of obtaining inherent strain, stiffness-ratio of welded region to adjacent region is needed. A stiffness-ratio can be obtained under even complicated modeling by using unit-force method [7]. Besides, stiffness-ratio for line heating problem can be simplified through leading researches [8]. But it is tangibly impossible that an analyzer obtains every stiffness-ratio at whole welded region.

To revise calculating stiffness-ratio, Elasto-plastic strain-boundary condition (EP-SDB) method based on thermal strain was developed using stiffness of FEM modeling. It makes shrinkage not of perfect elastic element by inherent strain but of elastic-plastic element by thermal strain. Like this, effects of constraints by adjacent region occur automatically. The existing inherent strain can reflect material hardening [9] and phase transformation [8]. For material hardening, the proposed method uses slopes of plastic curves, and for phase transformation, it uses thermal strain containing transformation strain and final transformed yield stress at stress-strain curve.

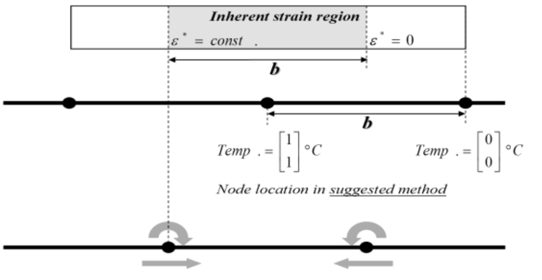


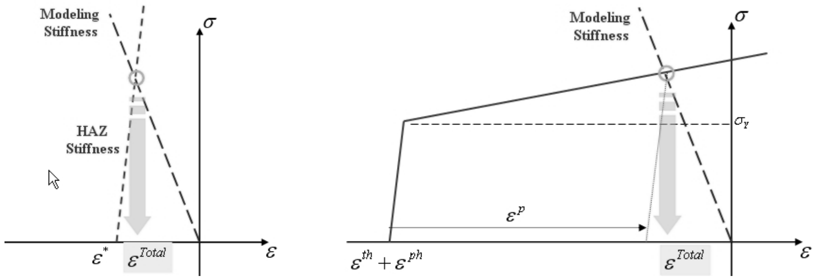
Fig. 1. Element size and temperatures standard in SDB analysis

3. Characteristics of INCONEL

As for the methodology EP-SDB analysis has 5 input parameters. These are thermal strain (negative, '0' at melting point), final transformed yield stress, equivalent maximum plastic strain, ratio of tensile stress to yield stress and elastic modulus (yield as 0.2% offset). These values can be obtained from Mill Certificates containing yield, tensile, elongation, thermal expansion coefficient (not always) and melting point (not always). This study deals with Inconel weld material, so that it is compared to another weld material having same yield stress for normal steel as given in Table. 1.

Table 1. Typical deposit characteristics & Chemistry of weld metals (Yield Strength = 524 MPa)

	625 LI-T1 (for Inconel)	DW-100KS
Tensile Strength	807 MPa	608 MPa
Elongation	35 %	28 %
Thermal Expansion Coefficient.	12.8 μm/m ℃	14.5 μm/m ℃
Melting Temperature	1290 ~ 1350 ℃	1420 ~ 1534 ℃



(a) Elastic analysis based on inherent strain (b) EP analysis based on thermal strain

Fig. 2 EP-SDB analysis concept [2]

This study use Inconel 625 series (Stoody 625 LI-T1) [10] (Special Metals, 2006), and it comes under TNi6625-1 1/4 and ENiCrMo3T1-1/4 of A5.34-2007 following AWS. Inconel 625, which is nickel-chrome-molybdenum alloy within Niobium, has high strength without heat treatment and resistance under extensive severe corrosion. The weld material inheriting those characteristics can be welded by any position under 100% CO2 or Argon/CO2-gas mixture. It has excellent weldability and can be applied to cladding and similar/dissimilar material welding.

Fig. 3 [10] shows that Inconel can maintain its properties at high temperature. Considering that yield stress of steel is nearly zero at 700~800℃ (mechanical melting point of steel), it is very impressive that yield of Inconel at same condition has over 80% of it at room temperature. Stress-strain curves from Table. 1 is shown at Fig. 4. This comparison gives two kinds of information about thermal distortion. These are thermal strain and hardening coefficient. They let me hard to answer which weld material makes more distortion and stiffness of adjacent region should be always checked for an answer.

The first dissimilar point is the thermal strain multiplied by melting point and thermal expansion coefficient. Under that '0' standard (cross point of two axes in Fig. 4) is melting point of weld material , lower thermal strain of Inconel makes smaller left moving of stress-strain curve than that of steel during cooling. It is more conspicuous when compared to austenitic steel having more thermal expansion coefficient than normal ferrite steel.

The second dissimilar point is the very high ratio of tensile stress to yield stress of Inconel. As it makes hardening coefficient high, the residual stress would be high after yielding. These two characteristics decide qualitative distortion aspects according to relation with adjacent region to weldment. Fig. 4 helps to understand the relation by redrawing axisymmetrically [8] as dot-dash line about strain axis. The cross-points of SS-curve and redrawn adjacent curve show total strains under each circumstances.

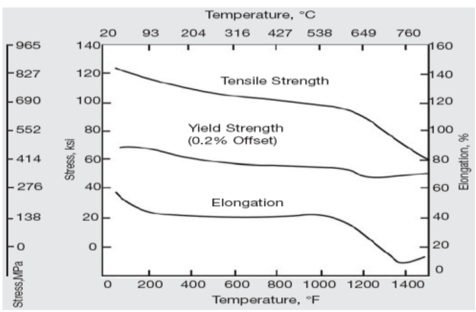


Fig. 3. High-temperature tensile properties of transverse specimens of INCONEL alloy 625 welds [10]

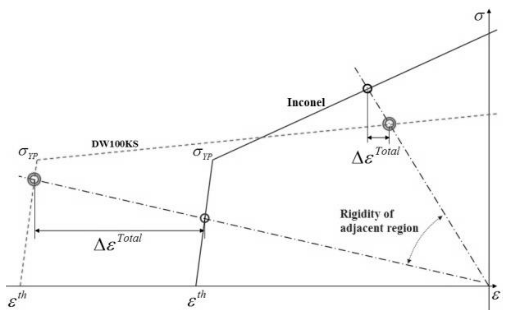
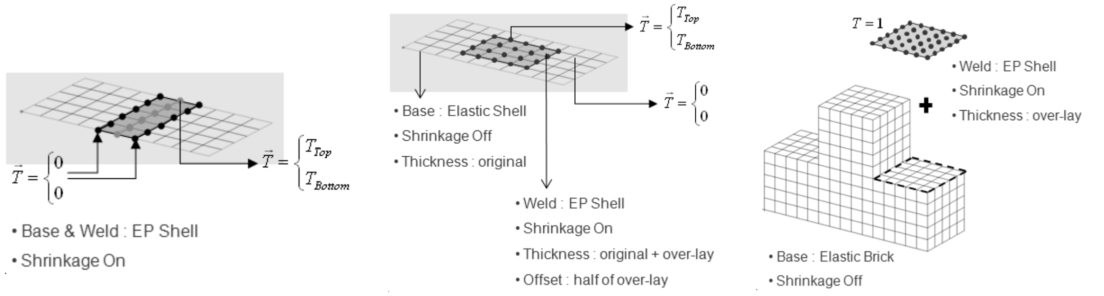


Fig. 4. Stress-Strain Curve for Inconel (compared with DW100KS)



(a) 2D Shell element only (normal welding & heating) (b) 2D Shell element only (over-lay) (c) 3D Solid Element + 2D shell over-lay element

Fig. 5. Concepts of thermal distortion analysis by over-lay

The case that the slope of adjacent stiffness, whose absolute value is small, means little resistance like transversal shrinkage of simple butt-welding specimen. As the distance between circular cross point (○:Inconel, ◎:Fe-based weld material) and stress axis means final deformation, it can be inferred that Inconel has less distortion. By the way, the over-lay is welded on existed structure, and over-lay thickness is much thinner than that of plate needing welding in general. That is, over-lay case has very high stiffness of adjacent region in Fig. 4. Fig. 4 shows that Inconel makes more distortion by its tensile than Fe-based weld material. In other words, even though a workman has many experiences about over-lay distortion with Fe-based weld material, dealing with Inconel should be another problem at least in accuracy control of welded structure.

4. Describing Over-Lay Analysis

The basic strain-boundary condition method for welding & heating assumes non-section change by transient-static. Therefore, elements containing welding nodes having imaginary temperatures according to layers must have same transversal mesh size. For a good reflection of that shrinkage by welding is concentrated at center of welding line, zero-degree boundary conditions are given at nodes of transversal both sides of welding nodes (Fig. 5 (a)).

This study tried to analyze thermal distortion by over-lay, prepared two strategies, and dealt with two kinds of examples in this text. The first is the case of large shell structure modeling like ship hull. It is efficient to subtract surface information from CAD system for ship block size or more. At first, additional thickness is added on over-lay region by over-lay thickness. Next, element offset is given by half of additional thickness. At last, imaginary temperatures from Eq. (1) by Eq. (2) [5] are given (Fig. 5 (b)) at welding nodes. In the case of many nodes on over-lay area, because over-lay boundary lines do not need to be strict, elements at the non-weld region are not given thermal shrinkage function, instead of zero temperature boundary condition. This procedure is used at moonpool structure analysis in this research.

$$T_{top} = \frac{1}{Mesh \cdot h} \cdot \int_{-\frac{h}{2}}^{\frac{h}{2}} b(z) \times (1 - \frac{4z}{h})\, dz \qquad (1)$$

$$T_{bottom} = \frac{1}{Mesh \cdot h} \cdot \int_{-\frac{h}{2}}^{\frac{h}{2}} b(z) \times (1 + \frac{4z}{h})\, dz$$

Where, Mesh : mesh size (mm)
h : plate thickness (mm)
z : thickness direction
(origin → neutral axis)
(+ : Top → Bottom)
b : bead & HAZ breadth (mm)
ho : over-lay thickness (mm)

$$\begin{aligned} & b(z) \rightarrow Mesh \\ & h \rightarrow h + ho \\ & \int_{-\frac{h}{2}}^{\frac{h}{2}} \rightarrow \int_{-\frac{h+ho}{2}}^{\frac{h-ho}{2}} \end{aligned} \qquad (2)$$

$$T_{top} = \frac{1}{h+ho} \cdot (ho + \frac{2h \cdot ho}{h+ho})$$

$$T_{bottom} = \frac{1}{h+ho} \cdot (ho - \frac{2h \cdot ho}{h+ho})$$

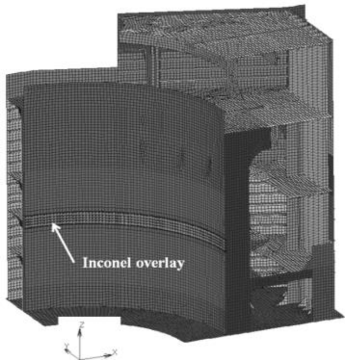
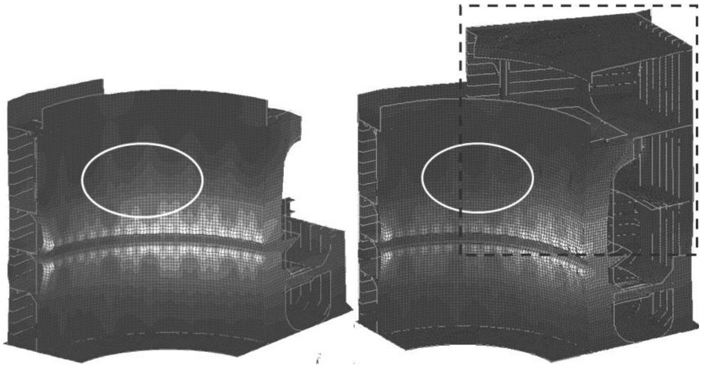


Fig. 6. Moonpool structure containing Inconel over-lay (1/4 modeling)



(a) Original Mega-block Plan (b) Revised Mega-block Plan

Fig. 7. Deformed shape of moonpool structure due to Inconel over-lay

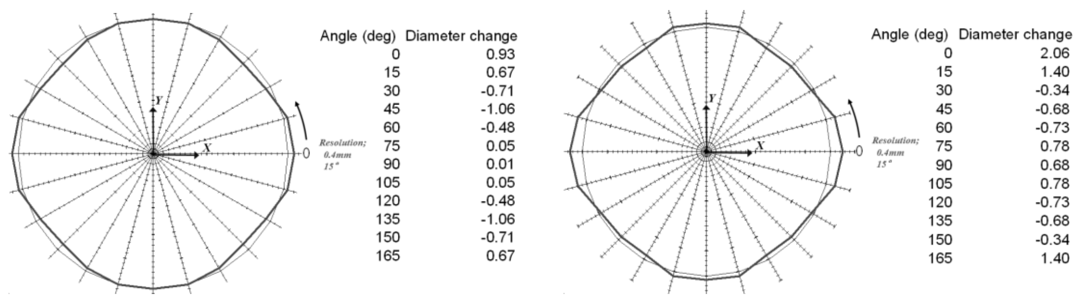
The second kind of example uses 3-dimensional solid elements in the case of small modeling or something hard to describe by shell element. In that case, shell element having over-lay thickness will be merged at over-lay region in solid modeling (Fig. 5 (c)). Because the shell elements describing over-lay has their real thickness, there is no need to calculate any boundary imaginary temperature, but to give ‘1’ degree. The solid model will not have the thermal shrinkage function. In this research, this methodology was used at over-lay at inner pipes to predict radius change.

5. Over-Lay Analysis Of Moonpool Structures

The first manufacturing problem may be roundness when over-lay welding is needed at a moonpool structure. Fig. 6 shows an example of Inconel over-lay welding position (bearing touching position) at a moonpool structure. If some people worry about the roundness after over-lay, they can make more rigidity by adding blocks (Fig. 7 (b)) before over-lay. But enlarged ship block will increase crane cost at moving a dock, so that just a worry cannot decide a moonpool block size.

An over-lay simulation was done to make a decision of a proper moonpool block size. Fig.7 shows results of over-lay simulation. We can see the less region of distorted inner wall at moonpool structure. Without simulation, anybody can figure out the less distortion under the more rigid structure, but nobody can predict how much. Fig. 8 shows diameter changes at special heights in mm unit under revised plan (Fig. 7 (b)).

To maximize promising the analysis based on elastic-plastic material, the process of installing/dismantling jigs (Fig. 9) was reflected in simulation. Jigs are normally installed at only assembly stages and erection stages to prevent from structural-thermal distortions. Because an analysis done by elastic material elements based on inherent strain makes any plastic residual stress field, the restraint effect cannot be assessed.



(a) 3,100mm (A/B, above bottom) (b) 9,800mm (A/B, above bottom)

Fig. 8. Thermal distortion analysis results at moonpool structure

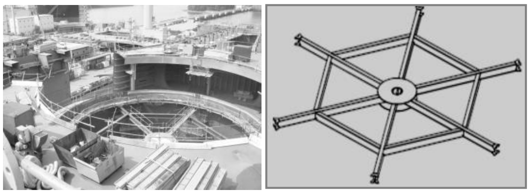


Fig. 10. Modeling of over-lay at inner wall in pipes

Though the analysis result is shown by 15°, the definition of roundness is the diameter difference between 0° and 90°. A positive roundness means the more shrinkage at 90° direction. Fig. 8 shows roundness of 0.92mm (3,100mm above bottom) and 1.38mm (9,800mm above bottom) at each height. The added blocks are located in upper and fore-aft region, so the positive roundness and the more value at the higher height can be understood. The final measured roundness at moonpool structure is 1mm. It shows good agreement with the simulation result.

6. Over-Lay Simulation of Inner Wall at Pipes

The In general, a corrosion-resistant pipe is not made by whole nickel alloy but is welded by over-lay at inner wall. In this case, shrinkage is also not avoidable, and lessened distances between bolt holes are most severe problems in the view of accuracy. Therefore, suggested simulation can make high productivity by reverse design of bolt-hole location considering thermal distortion and omission of remaking holes.

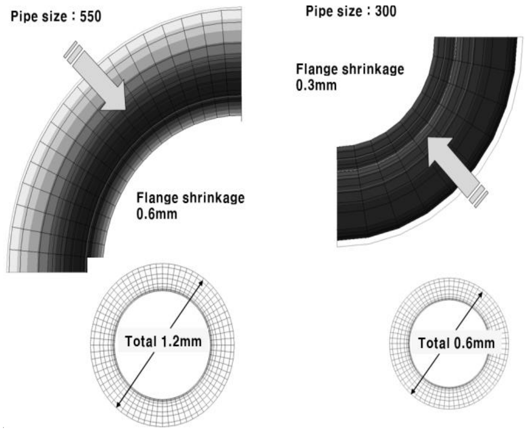


Fig. 11. Thermal distortion analysis results at moonpool structure

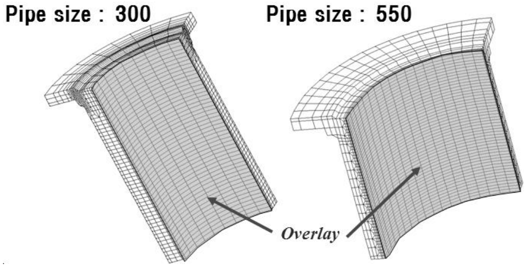


Fig. 9. A large hexagonal jig for roundness deviation

Fig. 10 shows modeling of pipe and over-lay at inner wall. In this modeling process, pipes are modeled by solid element and over-lay materials are modeled by shell element. Shell element has its real buttered thickness, and their nodes are merged to pipe models. The number of degrees of freedom between shell and solid is different, but it will not make any problems since there is no need to transfer moment from shell (over-lay) to solid (pipe). Fig. 11 shows the analysis results. The locations of bolt-holes are controlled before welding by analysis results, and there was no additional revising bolt-hole location after welding. In this research, Msc.Marc2012r1 is used by pre-processing and solver.

7. Conclusions

In this research

1. Why the Inconel over-lay is needed is described.
2. A methodology that makes high productivity in naval architecture is suggested under the case that distortion by over-lay can be predicted.
3. To reflect the material character of Inconel in analysis, the elastic-plastic strain boundary method based on thermal strain is suggested.
4. Inconel weld material and normal Fe-C weld material are compared in the view of distortion according to constraints.
5. Two examples are introduced. One is moonpool structure modeled by shell element, and the other is pipe inner wall modeled by solid elements.

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