1. Objective

The objective of the guidance note is to identify the factors that influence distortion in welded ship fabrication and offer solutions to control or minimise such distortion. The ultimate objective is to make the Australian fabrication industry more competitive by improving the quality of welded products and reducing fabrication costs.

2. Introduction

Shipbuilding involves the fabrication of large and complex welded structures. Hulls are made up from many plates joined by butt-welding with bulkheads and stiffeners welded to the inside surface only. Controlling distortion and maintaining overall dimensions of large panels is critical to the success of shipbuilding. The current trend to optimised designs using thinner plates and lighter stiffening creates greater challenges in managing distortion.

Distortion in the vicinity of welded joints is a natural and inevitable consequence of the non-uniform heating and cooling that occurs during the welding thermal cycle. This note identifies the factors affecting distortion and provides some brief guidance to Fabricators on practical approaches to controlling and correcting distortion during the fabrication of metal structures.

3. How Distortion Occurs

Thermal distortion occurs when a process generates thermal gradients resulting in strains, due to non-uniform expansion or contraction, that exceed the local yield point of the material. During the rapid heating cycle of a fusion welding process, material in the vicinity of the weld heats, expands in all directions and is compressed by the constraints of the much larger and cooler surrounding structure. The heated volume has a lower yield point than the cooler surrounding structure and is more readily upset to a smaller dimension, i.e. the heated volume yields in compression. On cooling, the weld deposit & the heated volume of the adjacent parent material contracts in all directions, creating tensile strains that are constrained by the attached cool structures that did not reach a yield point strain during the entire heating and cooling process. This localised contraction results in buckling, localised tensile yielding, or development of residual stress. On thinner members localized buckling will occur. On thicker members less localised distortion is evident, however residual stresses tend to be higher.

For a structural steel with a yield point of 250 MPa, a thermal differential of just 100°C will result in a thermal strain that approaches tensile yield point under fully constrained conditions. For a structural steel with a yield point of 400 MPa, a thermal differential of 160°C will result in a thermal strain that approaches yield point under fully constrained conditions.

The volume change of a structural steel weld during a fusion welding cycle occurs in two parts. Firstly the molten weld volume reduces by approximately 3% on solidification. We see this solidification shrinkage as craters at weld run terminations. Secondly the volume of the of the solidified weld metal reduces by a further 7% as its temperature falls from the melting point to room temperature. These two volume changes always occur and distortion control depends on developing an understanding of how to manage the process to minimise any detrimental effects.

4. The Main Types of Distortion

On heating and cooling metals expand and contract according to their expansion coefficient with expansion and contraction occurring in all three principal axes. Usually expansion in the through thickness direction is unconstrained, but there is constraint in the transverse and longitudinal directions.

Distortion can be categorised into six main types, i.e. longitudinal shrinkage, transverse shrinkage, angular distortion, bowing and dishing, buckling, and twisting.

4.1. Longitudinal shrinkage

Shrinkage stresses leading to a shortening of the member along the principal axis of the welded joint.

4.2. Transverse shrinkage

Shrinkage stresses leading to a shortening of the member across the toes of the welded joint

4.3. Angular distortion

Weld zone transverse shrinkage stresses not in the plane of the neutral axis leading to rotation of one member with respect to an adjacent member.

4.4. Bowing and dishing

Shrinkage of edges or surfaces where the distortion is not coincident with the neutral axis of the member leading to bowing or dishing due to asymmetric shortening

4.5. Buckling

Similar to bowing and dishing but more pronounced localised deformations as seen on larger structures or thinner or less restrained sections.

4.6. Twisting

Seen in slender structures with shear deformation at welded joints. Box sections and fabricated beams and columns can twist.

5. Factors Affecting Distortion

If a metal component was uniformly heated and cooled there would be uniform tri-axial expansion during heating followed by uniform tri-axial contraction during cooling and no thermal distortion evident upon return to ambient temperature. If the same heating and cooling cycle were repeated on a component that contained residual stress or was subject to significant externally applied forces (or constraints to thermal expansion or contraction), there would be distortion evident.

The principal factors influencing the type and degree of distortion are:

5.1. Parent material properties

5.1.1. Thermal expansion coefficient

This is the amount of expansion (or contraction) in a material as it is heated (or cooled).

The symbol for linear thermal expansion coefficient is *α*, and is expressed as [mm/(mm·K)] – strain/Kelvin

Carbon steel (α_{Steel} = 12x10 $^{-6}$/°K) expands less than stainless steel ($\alpha_{Stainless\ steel}$ = 17.3x10 $^{-6}$/°K), which expands less than aluminium ($\alpha_{Aluminium}$ = 23x10 $^{-6}$/°K).

- Lower thermal expansion ⇒ lower distortion
- Higher thermal expansion ⇒ higher distortion

5.1.2. Specific heat per unit volume

Specific heat, *c*, is the amount of energy required to raise the temperature of one kilogram of the substance by one kelvin and is expressed as expressed as [J/(kg·K)] – joule per kilogram Kelvin.

- Lower specific heat ⇒ lower distortion
- Higher specific heat ⇒ higher distortion

5.1.3. Thermal conductivity coefficient

The coefficient of thermal conductivity, *k*, is a measure of the rate *Q* (W) at which heat flows through a material and is expressed as [W/(m·K)] – W = Watts, m = metres, K = degrees Kelvin.

- Lower conductivity ⇒ lower distortion
- Higher conductivity ⇒ higher distortion

5.1.4. Yield point and yield point at elevated temperatures

The yield point is the limit of elastic behaviour where any increase in strain (or stress) causes permanent deformation. The yield point is expressed as a stress, *σ*, expressed as MPa.

- Higher yield ⇒ lower distortion, higher residual stress
- Lower yield ⇒ higher distortion, lower residual stress

5.1.5. Melting point

The melting point is the temperature at which a metal becomes liquid and is expressed as °C.

- Lower melting point ⇒ lower distortion
- Higher melting point ⇒ higher distortion

5.2. Level of restraint

Highly stiffened (restrained) structures offer better resistance to distortion during welding. This in turn leads to higher residual stresses and requires the weld zone to yield during the heating and cooling of a weld cycle, placing a higher demand on weld metal and HAZ properties.

- High restraint ⇒ lower distortion, higher residual stress
- Low restraint ⇒ higher distortion, Lower residual stress

5.3. Joint design

Joint design has a significant bearing on distortion. Shrinkage is directly proportional to weld metal volume so welds should be kept as small as practical.

Wherever practical symmetrical joint designs should be used. Balancing of shrinkage forces is important in minimising angular distortion.

- Minimal weld volume and symmetrical shrinkage forces ⇒ lower distortion
- Larger weld volume and asymmetrical shrinkage forces ⇒ higher distortion

5.4. Component fit-up

Good fit-up of components reduces the potential for movement as gaps close during welding and also minimises weld volumes.

- Precise fit-up ⇒ lower distortion
- Poor fit-up ⇒ higher distortion

5.5. Welding procedure

5.5.1. Heat input

- Lower heat input ⇒ lower distortion
- Higher heat input ⇒ higher distortion

5.5.2. Welding sequence

- Balanced welding sequence ⇒ lower distortion
- Unbalanced welding sequence ⇒ higher distortion

5.5.3. Preheat temperature

- Higher preheat ⇒ lower distortion
- Lower preheat ⇒ higher distortion

5.5.4. Eliminating re-work

Re-work introduces additional thermal cycles in both removal and replacing defective welding. Additional welding to rectify undersize welds can significantly increase distortion so it is vital to get weld sizes correct first time.

6. Preventing Distortion By Good Design

Good design incorporates principles that reduce the detrimental effects of weld zone shrinkage and underpins good workshop practices.

6.1. Design principles

Implementation of the following design principles should be considered to minimise distortion in welded structures.

6.1.1. Elimination of Welding

Welding can often be eliminated by:

- Utilising plates and profiles in the largest sizes available thus reducing the frequency of joining.
- Forming plates rather than cutting and welding.
- Using rolled or extruded sections rather than welded sections.
- Using stiffeners, thus allowing reductions in weld sizes.

6.1.2. Weld Placement

The location of welds as close as possible to neutral axes is important in minimising distortion. The closer a weld is to the neutral axis of a member, the lower the leverage effect of the shrinkage forces and hence the final distortion.

6.1.3. Reducing Volume of Weld Metal

Since weld shrinkage is proportional to the volume of weld metal it follows that the smaller the total volume of weld metal deposited the smaller will be the overall contraction during cooling and hence reduced distortion. Details of weld preparations and welding process selection should aim for the minimum weld volume consistent with satisfying the design strength and weld quality requirements.

A large fillet weld may be replaced by an incomplete penetration groove weld and smaller fillet to achieve the same effective throat thickness with a significant reduction in weld volume. Increased cost in preparation of the bevel has to be considered.

A double V plate butt weld has approximately half of the weld volume of a single sided V plate butt weld. The trade off is the additional cost in preparation of a double V preparation, the need to access both sides for welding and the possibility that rotating the part may be impractical, costly or time consuming.

It is worthwhile when distortion is an issue to review weld detail designs and ensure that specified weld sizes are not greater than necessary.

6.1.4. Reducing the Number of Weld Runs

Where possible use intermittent rather than continuous welds. Stagger intermittent fillet welds.

For complete penetration joints that require multiple weld passes to fill the groove, the larger the volume of each weld deposit the lower the distortion in the lateral direction. Paradoxically the use of a higher number of smaller passes can lead to a reduction in longitudinal distortion. This is because of the substantially greater longitudinal rigidity especially of thicker plates and hence the greater tendency of a smaller bead to yield longitudinally compared to a large bead.

The implementation of modern mechanised high-energy processes for single sided complete penetration welding of plates offers major advantages in reducing distortion as well as the obvious productivity gains.

6.1.5. Use of Balanced Welding

Wherever practicable, and particularly on thicker sections, use double side joints and a balanced welding sequence. This approach can be applied where components are small and rotation is practical.

7. Preventing Distortion by Fabrication Techniques

Workshop personnel have control over a number of activities as follows:

7.1. Precision in Marking Out and Cutting

Modern shipyards are utilising CAD/CAM in their laser and plasma cutting operations. The same equipment is now increasingly used for component identification and marking out. Marking out for subsequent assembly as part of the CAD/CAM cutting process minimises subsequent requirements for marking out, greatly reduces errors in marking out and improves assembly times.

This enables:

- High accuracy in cutting leading to good fit up in the fabrication shop, leading to less minor corrections and accompanying distortion.
- Identification of parts and marking out of cut pieces using dot matrix, laser or plasma systems. This leads to greatly enhanced traceability of parts, enhanced precision of assembly, minimising errors and rework.

7.2. Precision in Weld Preparation

Preparation of bevels for plate butt welds is now commonly by machining. While machining is more expensive than thermal cutting it enables compound bevels to be produced with precision not achievable by thermal cutting processes. Extremely accurate fitment of parts to be joined can be achieved. This is particularly important for larger welds such as main plate butt welds where major gains can be made in controlling overall distortion.

7.3. Precision in Assembly

This is where it all comes together and precision in assembly is dependent on accuracy of design, accuracy of cut parts, accuracy of marked assembly lines and last but not least the skills of the people doing the assembly.

7.4. Tack welding

Tack welding plays a critical role in firstly holding the assembled structure together ready for welding and secondly in maintaining correct root gaps in butt welds and preventing movement in the structure as welding progresses.

The number of tack welds, the length tack welds and the distance between them will depend on the length and thickness of the weld, the degree of rigidity needed, the details of the weld preparation and the welding process being used.

The tacking sequence can also have an effect and may need to be controlled to ensure correct root gaps are maintained along the length of a joint.

7.5. Back-To-Back Assembly

Back to back assembly of identical asymmetrical structures provides a method of counteracting the shrinkage forces of one component with the shrinkage forces of another. Additional presetting may be required so that when the two components are freed from each other there is no residual distortion due to spring back from locked up residual stresses.

7.6. Stiffening

Stiffening of a structure can be achieved in a number of ways. Use of larger tack welds, partially welding, provision of temporary bracing, use of assembly jigs with preset camber can be used to minimise distortion of a weldment. Longitudinal stiffeners welded along each side of a long seam can be used to prevent bowing of long members.

Stiffener location is important. If stiffeners are too far from the joint they are stiffening they may be ineffective, whereas if stiffeners are too close they may interfere with welding of the joint.

7.7. Pre-setting

Where a known amount of angular distortion will occur, presetting the joint by the amount of angular distortion expected ensures the alignment of the finished weld. This method can be very effective if consistent shrinkage rates are achieved through close control of welding procedures.

7.8. Jigs and Fixtures

Jigs and fixtures can be used for assembly and welding of subassemblies where the components are held rigidly until welded.

This approach works well for production of multiple smaller sub-assembles.

7.9. Welding

7.9.1. Welding Process

Higher energy processes that allow higher welding speeds generally lead to lowering of shrinkage and distortion rates with the advantage of increased welding productivity. Implementation of processes enabling higher welding speeds may be difficult to justify solely on the basis of reduced welding time, but overall savings can be significant when the downstream costs of distortion correction are considered.

7.9.2. Controlled Welding Procedures

Ensuring all operators are following welding procedures ensures that weld metal shrinkage is consistent. Maintaining consistency in shrinkage outcomes requires good welding management systems. Welding procedures should be developed to ensure that minimal weld metal is deposited while maintaining the specified weld quality level.

When carrying out the fabrication it is important that the weld sizes are produced within the specified size range and weld shape is correct. Over-welding of thin structural sections is common although there is no advantage to the fabricator or customer in over-welding. On the other hand, undersize welds can lead to costly re-work with inevitable increased distortion.

7.9.3. Welding Technique

General rules for minimising distortion are:

- Keep weld volumes/size to the minimum specified

- Balance welds about neutral axes
- Keep the time between runs to a minimum
- Maintain preheat temperatures

7.9.4. Welding Sequence

The direction and sequence of welding is important in distortion control. Generally welds are made in the direction of free ends. For longer welds, back-step welding or skip welding is used.

- For back-step welding short weld lengths are placed with welding in the opposite direction to the general progression.
- For skip welding a sequence is worked out to minimise and balance out shrinkage stresses.

8. Correcting Distortion

Whilst the aim of this guidance note is to provide information to minimise distortion, the following is to assist a fabricator in the techniques of distortion correction.

8.1. Mechanical Techniques

The following techniques rely on applying a force to change the shape of a component to correct the distortion produced by welding.

8.1.1. Hammering and Peening

This is a simple, cheap and sometimes effective method of correcting minor distortions. Hammering has limited application because it can lead to local surface damage and work hardening.

Peening of welds is an effective means of countering distortion due to weld metal shrinkage. Peening is carried out progressively as each weld or layer of weld is deposited in a multi-layer welds. The surface of the weld is spread out to reduce the tensile shrinkage stresses across and along the joint. Peening must be done carefully to avoid introduction of undesirable features on the peened surface and is not allowed by some fabrication codes.

8.1.2. Dogging and Wedging

This method may be effective to correct minor distortions where hammering alone is ineffective, enabling greater forces to be applied by using wedges. Care must be taken in the attachment and removal of dogs. Attachment points can provide sites or defects and may be restricted by some fabrication codes.

8.1.3. Pressing

Hydraulic presses can be used to correct distortion in the form of bowing and angular distortion. This approach is limited by the size of press available and the size and complexity of the component. Distortion can be corrected progressively, and with care there will be minimal damage to component surfaces.

8.1.4. Hydraulic Jacking

Hydraulic jacking is a variation on the dogging and wedging approach but offers more control and higher forces.

8.2. Thermal Techniques

Thermal techniques are based on creating compressive yielding at locally heated sites, which then provide a tensile stress to “shorten” the heated zone. The part to be shortened is rapidly heated to generate a temperature gradient with thermal strain sufficient to cause compressive yielding as it expands against the surrounding cold, higher yield strength metal. When the heated area cools the part that underwent compressive yielding contracts to a smaller size than before it was heated.

This is similar to the process that is described in Section 3 above, explaining how fusion welding causes shrinkage and distortion. The essential difference is that thermal techniques restrict the peak temperatures to below the temperature where metallurgical phase changes occur. In the case of CMn steels it is preferable that temperatures are kept below 720°C.

Further information can be found at (REF TO Krishna Verma information)

9. Summary

Some of the factors controlling distortion of welded fabrications have been identified. Adopting best practice principles can have significant cost benefits.

- Reduce the effective shrinkage force

    - Eliminate welding by forming the plate and using rolled or extruded sections
    - Use welding processes that deposit the weld metal as quickly as possible, i.e. minimising overall heat input
    - Minimise the amount of weld metal
    - Avoid over welding
    - Use correct edge preparation and ensure good fit-up
    - Minimise weld passes
    - Place welds near the neutral axis
    - Use intermittent welds
    - Use "back-step" welding sequence
- Utilise shrinkage forces to minimise distortion
    - Locate parts with angular preset
    - Make parts slightly oversize and pre-set parts so that welding distortion will achieve overall alignment and dimensional control with the minimum of residual stress
    - Pre-bend joint edges to counteract distortion and achieve alignment and dimensional control with minimum residual stress
- Balance shrinkage forces with other forces
    - Use tack welds to set up and maintain the root gap
    - Balance welds symmetrically about a neutral axis, e.g. double vee butt welds welded alternately from each side. Components set up back-to-back
    - Use of longitudinal stiffeners to prevent longitudinal bowing in butt welds of thin plate structures
    - Use jigs and fixtures, flexible clamps, strong-backs and tack welds to apply restraint during welding. Consider the risk of cracking which can be quite significant, especially for fully welded strong-backs. Welds for temporary attachments for restraint should be made using an approved procedure and may require preheat to avoid forming imperfections in the component surface.
    - Peening to stretch the weld metal and reduce local shrinkage forces

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NDNP TECHNOLOGY DIFFUSION ACTIVITY # 27	WTIA Welding Technology Institute of Australia ABN 69 003 696 526 **NATIONAL DIFFUSION NETWORKS PROJECT** **TECHNOLOGY QUESTIONNAIRE** **Defence Industry Group** **“Distortion control in shipbuilding”**	**Document No:** 9.4.3QR-0001 **Revision No:** Rev 0 **Page 1 of 2** **Date:** 06 Mar 2006

As part of the WTIA National Diffusion Networks Project the Defence Industry Sector identified the need for guidance on the control of distortion in shipbuilding. The WTIA has prepared a Technical Guidance Note “Distortion control in shipbuilding” to help understand distortion in welded ship fabrication and offer solutions to control or minimise such distortion. As a valued technology expert in this area we would like you to be part of the Technology Expert Group to review this note. Please complete this questionnaire so that we can gauge the success of meeting this need.

Objective 1: Identify the factors that influence, and offer solutions to control, distortion

Ship designs are moving towards higher levels of design optimisation. This means thinner hull and frame plates and lighter stiffening members. Distortion control becomes more difficult on optimised structures. This guidance note is intended to identify the factors leading to distortion and identify the significant parameters that can be managed to control the level of distortion from welding. How well does the document explain the causes and corrective actions to control distortion?

poor ☐ average ☐ good ☐ very good ☐

Comments: ______________________________

Objective 2: Identify appropriate technology receptors in the Defence Industry

This document was written for Designers, Fabricators and Maintenance practitioners in the Defence Industry. Are these people the appropriate individuals we should be targeting?

yes ☐ no ☐

What other types of companies and/or personnel do you suggest we target? ______________________________

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Objective 3: Identify best practice

The document was written to reflect current best practice and latest technology for minimising distortion. Do you envisage opportunities for the use of this technology in the industry?

yes ☐ no ☐

If yes, what and where, if no why not? ______________________________

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Objective 4: Is the information provided clear, concise and accurate?

yes ☐ no ☐

If not, why? ______________________________

Objective 5: Broad dissemination of technology to the Defence Industry

Please indicate how best to disseminate this Technical Guidance Note to the appropriate Defence Industry Recipients

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If poster, what size? A1 ☐ A2☐ A3 ☐ Laminated ☐ What selling price? $

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Other format? ______________________________

Objective 6: Continuous Improvement

Please Identify areas where the document can be improved or return the document with your recommended additions/amendments. Alternatively, please use the area below to provide any additional comments.

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Please Fax (02 9748 2858) or E-mail (b.gross@wtia.com.au) your response. Your prompt response is appreciated.

The WTIA has joined forces with industry and government to create a 3.5 million dollar Technology Support Centres Network. This network will assist industry to identify and exploit world's best technology and manufacturing methods to establish a vibrant Australian industry beyond 2006. Together we will be implementing a step by step process which will lead to ongoing viability and greater profitability for all concerned:

(1) Determine your technological and manufacturing needs;
(2) Identify world's best practice;
(3) Draw upon the network to implement world's best practice at your site