Assessment of Hot Cracking Initiation by Laboratory Test Procedures and FEM-Simulation Associated Experimental Measurements During Welding of Large Weld Components *

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The effects of material, welding procedure and weldment structure are used in the sense of joinability to analyse the complex problem of centreline solidification crack initiation during welding processing.

The hot cracking test procedures with externally loaded specimen, based on the theories of Prochorov and Matsuda (MISO-technique, PVR-test and Varestraint-/Transvarestraint-test), are only partly true for the assessment of centreline solidification crack initiation during welding. The measurable condition and quantifying criteria of the tests vary from one to the next. They require a complicated calculation of the theoretical function “strain-rate”.

A special measuring technique was developed, tried and tested to estimate the initiation of solidification crack in flat and large components. The combination of measurement and calculation was applied to put the reliability of new derived crack minimizing methods to the test with the help of the Finite Element Analysis (FEA) simulation. It takes into account the speed of cross displacement during welding processing, affected by weld component dimension and weldment assembly.

The critical speed of displacement during welding processing determines the crack criterion for that moment when the local initiation of a centreline solidification crack is prevented. That is, no hot crack is diagnosed after the welding. This is the case when the speed of displacement, released by fusion in front of the weld pool and thermal expansion during the welding process, is in equilibrium with the speed of displacement within the brittleness temperature range during solidification behind the weld pool.

The centreline solidification crack initiation is assessable by comparison of the critical speed of cross displacement in the welded material (determined by experiment) to the local speed of cross displacement in the weldment (calculation by FEA-simulation).

An assessment diagram for centreline solidification crack initiation during one-side welding was arrived at the multitude of results within displacement measurement during welding processing in flat and large components. It was utilized for a predictive assessment of solidification crack initiation of weldment depending on component dimension and welding procedures.

**Key Words:** Solidification Cracking, Test Methods, Hot Cracking Criterion, Welding Processing, Displacements, Measurement, FEA-Calculation, Large Weld Components, Hot Cracking Assessment

1. Introduction

Hot cracking at the plate end of large weld component are undesirable defects during welding processing. The occurrence of centreline solidification cracking is due to the liquid/solid state of the weld metal [1, 2, 3]. During the one-side submerged arc welding processing the liquid weld metal solidifies backwards and/or besides of the molten welding pool, while at the same time the heat input of the welding arc produces thermal displacements, deformation and shrinkage in the plates.

The features of high density heat input and large shrinkage have been studied experimentally for hot cracking prevention in the seventies by the Naval Architects in Japan, focussing on the effect of deformation behaviour, transient strain, the end cracking, its prevention, modelling and simulation by Finite Element Analysis (FEA) [4, 5, 6, 7, 8, 9, 10, 11, 12, 13]. In the eighties it has followed mostly experimental and simulative Japanese investigations in the effect of root gap changing during welding of butt weld joints [14, 15, 16, 17] with partial systematic and quantitative theoretical considerations. The results of welding shrinkage computed by FEA were compared with experimental results in the nineties, discussing the effects of local heating, welding sequences and constraint conditions on the transverse shrinkage of large plates [18, 19, 20, 21] as well as the effect of precision ship assembling. In spite of this, all these investigations describe and calculate the correlation between solidification cracking, heat input, welding processing and deformation fundamentally in detail, but they do not combine all among themselves to assess the hot cracking risk during one-side welding of real components.

The application of the joinability concept can guarantee centreline solidification crack-free welding processing due to complex investigation in displacements during one-side welding of longer butt weld seams in ship building industries [22, 23]. Joinability takes into account all the influences to a joined structure affected by the joining suitability for material, the joining capability for processing and the joining reliability for use and service. The origin of hot cracking during welding processing has been studied by theoretical and finite element analysis, laboratory tests, measurement of displacements during fabrication welding of real components, thus creating effective methods for hot crack-free one-side welding [24, 25].

The complexity of effects on hot cracking initiation has been classified by joinability aspects, resulting in a hot cracking criterion of the one-side welding processing of large components.

*Received 2003. 5. March
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This hot cracking criterion and the various results of applied experimental methods to prevent hot cracking was classified by speed of displacement to relate an assessment diagram[26] using the FEA to assess the effects of component design and assembly on hot cracking initiation.

The limits of quantifying hot cracking sensitivity by the laboratory test procedures have supported the development of a welding process associated test procedure for assessment of the critical hot cracking initiation during welding of large welding components [26].

2. Calculation of displacements during welding

The model to calculate the speed of cross displacement during welding in [22-25] with the help of FEA program ANSYS and experimental measurement bases on the thermo physical mechanics by a 2D model, ignoring the non equality near the melting point. The FEA program ANSYS [27, 28] calculates the temperature, displacement, stress and deformation as they occur in the large plates during the welding process. The model considers the time dependence of all thermal and mechanical effects during welding processing. These are the temperature dependent physical properties of the plate material (specific heat, thermal conductivity, expansion coefficient, convection, radiation), the welding parameters (welding current, welding voltage, welding speed) and the fixture conditions for the assembly (geometry of the plates, magnetic fixtures [70 kN/m], tacks [25 × 2 mm length per thickness at each 800 mm], run-out plates and their dimension). The mechanical properties of the material are fed into the model, as the temperature dependent stress-strain curve, in steps about 100-1400°C.

The model calculates the cross (transverse) displacements and their temporal changes at observed points along the weld bead during the welding processing as local speed of cross displacement \(v_q\) [mm/s].

The program calculates the speed of cross displacement \(v_q\) in figure 1 (combined figures at the bottom and middle diagram) for each of these points precisely at the time when the end of the weld pool [that is, the begin of BTR] passes the observed point. It takes into account the welding procedure (heat-input) in relation to the design and assembling for welding. Direction and amount of the flat displacements during one-side welding in the large component (figure 1, (sub-figure at the top) have favoured the cross displacement for investigation in initiation of centreline solidification cracking.

The speed of cross displacement \(v_q\) in figure 1 maximizes systematically when the arc comes near the plates end and the far side of the weld pool passes from the plate to the run-out due to the stiffness jump. It increases locally during fusion of each tack additionally releasing assembly stresses. These short and rapid increases of cross displacement with regard to time and versus to the welded seam are the most important factors to initiate centreline solidification cracking of longer butt weld seams.

Simulation of welding deformation [18-21] and thermal induced hot cracking effects [4-11, 22-25] has become important with the development of various FEA simulation techniques. [29] proposes another actual model for the formation of hot cracking, using temperature dependent interface elements, based on a surface problem with help of FEA. Therein the crack propagation is considered as the formation of new surfaces without taking into account the effects of temperature on the strength of the interface element.

3. Definition of a hot cracking criterion

The hot cracking criterion is defined on the basis of the speed of cross displacements during the welding processing considering the complexity of the welding processing in the weldment. The hot cracking criterion acts as the equilibrium condition for the classified effects on hot cracking initiation. It balances the material associated speed of displacement as the critical speed of cross displacement \(v_c\) with the design/assem-
bly associated local speed of cross displacement in the weldment $v_q$. The criterion for centreline solidification cracking follows from the combined diagram in figure 1 (middle). It takes into account the dynamics of welding processing with regard to the material and metallurgical effects as well as the component with the effects of design and assembly. The welding process acts at each point besides the weld bead with its same heat input, welding speed, weld pool shape, and diameter of electrodes, wire stick-out, welding sequence, preheating and post-weld heating on both the material- and component-associated effects. The fusion welding process affects the material and metallurgical reactions of the solidifying weld metal by alloying composition, gas/wire and flux/wire combination or shielding gases as well as the respond of the component and assembly for welding. The welding process causes a moving temperature field. It produces considerable displacements and distortions by the inhomogeneous thermal expansion of the locally heated plates in the heating phase and by the effects of design and assembly.

The critical speed of cross displacement $v_{cr}$ is the material and welding process associated property that keeps constant during the whole welding process. It summarizes the effects of the welding parameters on the solidifying welding pool. That are the shape and the effect of metallurgical composition of the arc fused welding pool on the backward solidification within the brittleness temperature range with its material ordinary sensitivity to hot cracking. Both reactions of the applied welding procedure do not change during welding processing along the seam in the weldment.

Otherwise acts the local speed of cross displacement $v_q$. It is affected by the thermal physical reactions of the weldment on the welding procedure with respect to design and assembly, e.g. stiffness jumps during passing of the welding arc from the large plate into the run-out, climbing by fixtures, dimensioning and yielding effects of the run-outs as well as the release of assembly stresses by fusion of tacks. Therefore the amount of the speed of cross displacement $v_q$ decides whether centreline solidification cracking is initiated or not, proved by non-destructive testing after welding.

The hot cracking criterion for the one-side welding of large components is based on the equilibrium of weld component (design/assembly) and welding process associated speed of cross displacement $v_q$ as well as on material (metallurgical) and welding process associated speed of cross displacement $v_{cr}$.

$$v_q > v_{cr}$$

Centreline solidification cracking occurs if and when the weld component and process associated speed of cross displacement $v_q$ grows higher than the material and welding process associated speed of cross displacement $v_{cr}$. The criterion for centreline solidification cracking demands a special test procures to determine the critical speed of cross displacement $v_{cr}$ considering the peculiarity of the one-side tandem submerged arc welding process of large components.

4. Test procedures

4.1 Laboratory test procedures to quantify hot cracking sensitivity

The practically applied hot cracking test methods are based on the global concepts of Matsuda [30] and Prokhorov [31] with measurable constitutional, mechanical, thermal and time-affected test criteria. The hot cracking theory by Prokhorov is based on a critical deformation rate for solidification cracking. The deformation rate is the $\frac{\partial \epsilon}{\partial T}$ within the Brittleness Temperature Range (BTR) in $[\%/\text{C}]$. Hot cracking appears when this deformation rate $\frac{\partial \epsilon}{\partial T}$ during solidification within the BTR is higher than the critical deformation rate. This theory is supported by a test method superimposing various defined strain rates perpendicular to the welding procedure to determine the critical deformation rate for solidification cracking empirically by a yes/no criterion of cracking.

The hot tensile test (Gleeble test) determines the hot ductility curve with both on-heating and on-cooling tests and highest experimental effort. Both the ultimate tensile strength and the reduction in area are plotted as function of the temperature.

The varestraint test and the trans-varestraint test assess hot cracking sensitivity by a diagram of total crack length versus applied surface bending strain. There are several variations all over the world for the test procedure of bending the flat specimen during a bead-on plate TIG welding.

During the PVR-test a welding process with constant welding speed is superimposed by a linearly increased tension speed $v_{PVR}$ in welding direction. This creative test method needs only one flat test specimen to determine the critical tension speed $v_{cr}$ for hot cracking initiation of the tested material during the applied welding procedure (solidification cracking in the base material and liquation cracking at fusion line and heat affected zone).

The recent test procedures of the main hot cracking tests are standardized [32]. The comparison of the results of these hot cracking tests shows [33] that there is a good consistency in cracking sensitivity of the materials tested, although the test procedures and test criteria are very different. The MISO technique [34] in Japan is similar to the hot cracking test by Prokhorov.

However, the laboratory hot cracking test results do not guarantee a crack-free fabrication welding of industrial products. The deficiency of conservative test procedures and their test results commented on above has supported the further development of a welding process associated test method as-
Assessing the hot cracking initiation during welding fabrication of selected products.

4.2 Welding process associated hot cracking test method

The investigation in centreline solidification crack-free one-side welding of large components [22-25] has requested the development of a special hot cracking test method (Figure 2) to quantify the local speed of cross displacement $v_q$ at two measure cross sections perpendicular to the welding direction near the plate end.

The measure device of the welding process associated hot cracking test method works with two special cross gauges, derived from the small fracture mechanical clip gauges for CTOD measurement. The cross gauges works with inductive length sensors measuring and saving the local cross displacements during the whole fabrication welding processing over the seam length of about 10 to 16 m long plates in ship building industries. The measure frequency is of about 50/s. The total cross displacement is summarized by the amounts measured with the sensors at the plate besides the seam. The speed of cross displacement $v_q$ is calculated as the temporal change of the measured cross displacements of the 10 mm thick plates for the applied tandem-submerged arc welding procedure with the FMI process [35] (welding arc I: current $I_1 = 730$ A, voltage $U_1 = 32$ V, wire OES-2, 4 mm diameter; welding arc II: current $I_2 = 680$ A, voltage $U_2 = 38$ V, flux cored wire 35.25 2D, 4 mm diameter, welding speed $v_w = 95$ cm/min using surface flux: OP122FB and water cooled weld pool back-up flux: OKFlux10.69).

The occurrence of hot cracking or the crack-free welding was examined by non-destructive weld inspection of fabricated seams after welding referring to the measured cross displacement and calculated speed of cross displacement. The critical speed of cross displacement $v_{cr}$ is the result of empirical approximation, characterising the applied tandem-submerged arc welding procedure. The developed assessment diagram realizes the empirical approximation.

4.3 Measurement of cross displacements

Figures 3, 4 and 5 show characteristic test results of the investigation of typical effects by designing and assembling for crack-free one-side submerged arc welding. A graduation in the horizontal scale is common for all sub-figures including the bottom one. The use of small run-out plates e.g. systematically produces hot cracking at the plate end (figure 3) when the end of the welding pool of the tandem-submerged arc welding process passes from the plate end into the run-out [1-4]. Figure 3 compares the calculated and measured speeds of cross displacement.

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Fig. 2a Measuring device with two special cross gauges measuring the cross displacement $u_y(t)$ versus time during one side welding of large components

Fig. 2b Principal measure of the cross displacement versus time during one-side submerged arc welding of large components with two special cross gauges
Fig. 3  Correlation between local hot cracking in the welded seam with the amount of measured and calculated speed of cross displacement during one-side submerged arc welding of large component. The test results in figure 4 explain that the synchronous heating of the external plate edges \( t_2, t_3 \) can minimize the increasing speed of cross displacement near the seam end due to the peculiarity of welding processing on large components and the stiffness jump by passing of the arc from the large plate to the small run-out. The locally heating of the external edges does minimize the cross displacement more intensively than the speed of cross displacement.

The melting of assembling tacks or passing of designing stiffness jumps can release tension stresses of the assembled component resulting in very short and rapid displacements. These locally affected cross displacements initiate hot cracking although the plates have been fixed by tacks, fixtures and run-out plates \( \text{figures 3-5} \). All the experimentally measured results during welding agree in the correlation between the effects of design and assembly of large component as well as the occurrence of

Fig. 4  Effect of locally dosed heating of the external plate edges to prevent centreline solidification cracking compared with measured cross displacement and speed of cross displacement \( v_{c} \) during one-side welding.

Fig. 5  Effect of stiffness-jump reducing run-out plates to centreline crack-free one-side welding compared with measured cross displacement \( u_{c}(t) \) and speed of cross displacement \( v_{c} \).
centreline solidification cracking quantified by the speed of cross displacement. The results prove that centreline solidification cracking in large components can be prevented by welding processing and welding assembling effects with respect to the criterion for centreline solidification cracking \( v_c < v_q \).

5. Assessment diagram for the initiation of centreline solidification cracking during one-side fabrication welding

The welding process associated test procedure measures the cross displacement \( u_c \) [mm] as function of the time and calculates the speed of cross displacement \( v_q \) with the help of FEA. However, the estimation of the critical \( v_q \) needs an empirical assessment diagram for determination of the critical speed of cross displacement \( v_q \) correlating to the applied material and welding process in figure 6.

The assessment diagram composes the complexity of hot cracking by three sub-diagrams. The assessment diagram for centreline solidification cracking is on the right side. The multitude of calculated curves of the weld component and process associated speed of cross displacements \( v_q \) measured with help of the welding process associated hot cracking test method are plotted here as cooling time of the weld metal versus the change of the measured and calculated cross displacement \( \Delta U \) (t) in [mm]. The critical speed of cross displacement \( v_c \) is defined here as the threshold curve, separating the regions with occurring hot cracking and crack-free regions, realizing the empirical approximation. The middle sub-diagram shows the correlation with the hot cracking theory by Prokhorov, setting up the internal deformation versus the temperature. The left sub-diagram contains the thermal cycle of the applied welding procedure. The correlation between measured \( \Delta u \) (t) and internal deformation by Prokhorov is defined in the figure below.

The assessment diagram is applicable in correlation with FEA simulation of large components, in order to develop new methods of crack-free designing and assembling for welding relevant and large components as well as for refining metallurgical effects and modifying welding procedures.

However, all variations in welding procedures will change the location of the threshold curve of the tested welding procedure, affecting the material and metallurgical effects as well as the component and assembling effects. This high sensitivity to welding procedure induced effects underlines the limited expressiveness of the laboratory test procedures in view of the reliability of the weldment.

Summary

1. Hot cracking is controllable by joinability, taking into account all the influences to a joined component affected by the joining suitability for material, the joining capability for processing and the joining reliability for use and service.
2. Centreline solidification cracking occurs if and when the weld component and welding process associated speed of cross displacement \( v_q \) grows higher than the material and welding process associated speed of cross displacement \( v_c \). It can be prevented by considering the criterion for centreline solidification cracking \( v_q < v_c \).
3. The calculation of the speed of cross displacement \( v_q \) with help of the FEA calculation takes into account the welding procedure in relation to designing and assembling for welding.
4. The laboratory test methods are not suitable for determining the critical speed of cross displacement \( v_c \), considering the peculiarity of the one-side tandem submerged arc welding processing of large components.
5. The welding process associated hot cracking test method works with two cross gauges measuring the cross displacements perpendicular to the welding direction during one-side tandem submerged arc welding procedure in prefabrication of ship building. There is a high agreement between both calculated and measured speed cross displacement \( v_q \).
6. The critical speed of cross displacement \( v_q \) is defined by an assessment diagram as a threshold curve of all measured speeds of cross displacement \( v_q \), separating the regions with hot cracking and crack-free regions. The assessment diagram is applicable in correlation with FEA simulation of large components for developing and proving new methods of crack-free designing and assembling for welding of large components.
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