Mechanical Characteristics Generated by Solidification Crack During High Strength Steel Welding

Z M Li and Z L Chen

School of Marine Engineering, Jimei University, 76th Shigu Road, Jimei District, Xiamen, China
Email: zhanglanchen@jmu.edu.cn

Abstract. A multiscale method was developed to elaborate weld solidification crack mechanical field. A sequential thermo-mechanical finite element method (FEM) of butt-joint was performed to provide both of geometry and loading condition of submodel. Then mechanical behaviours generated by impurity was achieved by submodelling with embedded solidification cracks in terms of elasto-plastic FEM. The solidification initial cracks were geometrical discontinuity in nature and modelled as mechanical property discontinuity. Results show that additive stress and back stress are built-up at impurity-weld matrix interface. The developed modelling method was validated by solidification crack tests, X-ray tests together with fractography. The underlying mechanisms in suppression solidification cracking by adjustment of alloy contents in flux cored wire aiming to diminish the impurity size and improve the ductility of weld metal were revealed by developed method. Results show that, given a 9 percent increase of the weld metal ductility, a 29.6 percent decrease of the additive stress is achieved; and the longitudinal oriented impurity readily propagates crossing section rather than along impurity longitudinal tip. The susceptibility to cracking is distance-dependent, heavily on fields near to impurity and little on far field.

1. Introduction

In recent years, high strength steels (HSSs) have experienced increasing application of modern shipbuilding and marine structures to meet the demand for light weight. HSSs usually comprise multi-phase microstructures produced by alloying and specific processing routes, which makes solidification cracking of HSS be one of the most important considerations in welding process [1].

Metallurgy factors are usually identified as source inducing solidification cracking, such as lack of fusion, concentration of P, S and considerable portion of non-metallic inclusions [2-4]. There is a sudden drop of low-melting-point phase and lack of fusion in mechanical performance during a temperature range from 850 °C to 1250 °C, named thermal brittle temperature range (BTR) in the course of welding. It is confirmed that increase of Mn content is effective to suppress solidification cracking by weakening the negative influence of Nb on cracking resistance to some extent [5].

As an affordable alternative to reveal the underlying reaction of thermal generated mechanical performance of weld components, numerical computation is employed to predict welding stress. Among numerical models, Ueda and Yamakawa [6] found thermal elasto-plastic finite element method (FEM) with considerable precision. Chen et al. [7] modelled the weld component with homogeneous material, although crack problem is related, ignoring the discrepancy of thermo-mechanical performance between the impurity and weld metal. In fact, as subjected to welding thermo-mechanical process, the impurity and the weld metal may strain plastic heterogeneously,
resulting in extra stresses at the impurity interface, which may be a main factor resulting in premature solidification cracking. Without accounting for this crack-resulted stress concentration, the conventional method based on homogeneous material is in doubt to be too conservative to predict solidification cracking. On the other hand, to detail the impurity nonlinear behaviour, the mesh which is fine enough with respect to welding thermo-mechanical prediction may be too coarse as referred to cracking analysis in fracture mechanics [8]. As opposed to coarse mesh, a finer mesh in welding thermo-mechanical evolution is time and computation unaffordable. It seems a compromise solution can hardly be found within the framework of a single thermo–mechanical FEM with cracked model.

Several parameters of strength and fracture mechanics were correlated with initiation of solidification cracking, such as the maximum transverse stress [9], transverse stress [4] and thermal strain [10-11]. Плохороб Theory attributes the hot cracking to metal ductility and plastic strain volume within the brittle temperature range. A two-parameter criterion (equivalent plastic strain and stress triaxiality) to analyse the effect of a geometrical discontinuity, strength mismatch on the critical condition for fracture initiation [12]. Chen et al. [7] assumed a crack embedded in weld surface, and predicted cracking using stress-intensity factors around crack tip as subjected to welding thermo-mechanical loading. Nevertheless, there is limited effort devoted in the parameters to characterize the impurity influence mechanism with respect to impurity free case.

Engineering strategies to avoid solidification cracking are frequently reported [3]. A double-layer hybrid welding process was proved to be effective to avoid a premature solidification cracking in laser-MAG welded 30CrMnSiA joints [4]. Nevertheless, the underlying mechanisms of those engineering strategies and the underlying physical origins are still a challenge for special HSS welding.

In terms of CO₂ gas shielding weld experiments of Q460 butt-joint in ship manufacturing engineering, where general routine of content adjustment of manganese and nickel to suppress the low-melting-point phase to avoid premature solidification failure was adopted. This study correlates experimental solidification cracking susceptibility to the sulphides phase in weld metal with submodelling involved numerical methodology, aiming at understanding the solidification crack susceptibility to impurity size, position and weld metal ductility as well. A heterogeneous weld metal model has been proposed and impurity behaviour has been elaborated.

2. Solidification Crack Experiment

Here consider the butt-welded configurations with a dimension of 50 mm × 300 mm and single V shape groove. 10 mm thick plates of HSS typical applied in ship and marine structure, Q460, were joined by CO₂ gas shielding welding in a sequence from No.1 to No.5, with total welding direction from right to left, as shown in figure 1. The specimen restrains were adopted as referred to the restrained Butt joint cracking test, which is typical in testing materials cracking sensibility. The ceramic backing used in experiment is Tiangao TG1.0Z. The welding parameters were: current 190-210 A, arc voltage 24-27 V, welding speed 240 mm/min, flux cored wire TWE-81K2 (satisfied with both standard requirement of AWS A5.29-2005 E81T1-KWC and GB/T17493-2008 E551T1-K2C) with a diameter of Φ1.2 mm (series: 16-9949), gas flow 15-20 L/min.

After welding, crater solidification cracks are observed. X radiographic tests were performed for crack dimension. Results show longitudinal linear cracks with various lengths at weld crater, as shown in figure 2.

**Figure 1.** Butt-welded configuration (unit: mm).
Crack specimens were sectioned transversely from the welding seam using electro-discharge machining (EDM), followed by an ultrasonic cleaner. Figure 3 shows the separated specimens. The fractography examination was performed by scanning electron microscope (SEM) Hitachi S-3700N, as shown in figure 3b. The presence of liquid film in the shrinkage distributes along grain boundary, indicating a typical solidification cracking mechanism. Fracture propagates along crystal boundary.

![Crack specimens](image1)

**Figure 2.** X radiographic test.

The nominal chemical composition of the plate and weld is obtained by EPMA (Electron Probe X-ray Microanalysis) and shown in table 1. The sulphur contain of weld metal is 0.013 %, a mass fraction higher than that of parent metal and far beyond the permitted 0.004%.

|                  | C   | Si | Mn | P   | S   |
|------------------|-----|----|----|-----|-----|
| **Plate**        | 0.17| 0.30| 1.18| 0.014| 0.009|
| **Weld metal**   | 0.031| 0.312| 1.01| 0.016| 0.013|

### Table 1. The chemical composition of the Q460D and weld metal (mass fraction, %).

3. Solidification Crack Suppression

To avoid the solidification cracking, parameter optimization was firstly attempted by tuning weld linear energy in the range of 11 to 20 kJ/cm, which made a limited difference. The mass fractions of metal element manganese and nickel in flux-cored wire were then tuned in an orthogonal routine from 1 percent with a spacing of 0.1% until the complete suppression of solidification crack. Two sets of butt-joint with optimized mass fractions show completely solidification cracking suppression. The set optimized by manganese element poses typical chemical composition in weld metal as table 2. As opposed to the manganese and sulphur contains listed in table 1, table 2 shows increased mass fractions of manganese and decreased sulphur content as low as 0.0063%.

As solidification crack suppressed, the strength of butt-joints needs to be known if those welds meet the demand of strength. Three specimens in each component sets for uniaxial tensile experiments were abstracted from butt-joint in terms of *tensile test methods on weld and deposited metal* (GB/T 2652-2008/ISO 5178: 2001). The mechanical parameters are shown in table 3, of which weld metal referred by TWE-81K2-1 was deposited by additional manganese; referred by TWE-81K2-2 was deposited by the combination by manganese and nickel. The weld metal deposited by TWE-81K2-
lends itself almost identical strength as parent plate, indicating identical strength match of welded joint. The elongation to fracture in weld metal deposited by TWE-81K2-2 case was improved with a slightly lower strength.

**Table 2.** The chemical composition of improved weld metal (mass, %).

|   | C   | Si  | Mn  | P   | S   |
|---|-----|-----|-----|-----|-----|
|   | 0.049 | 0.27 | 1.53 | 0.011 | 0.0063 |

**Table 3.** Mechanical performance.

|                | Yield strength $\sigma_y$ (MPa) | Ultimate tensile strength $\sigma_u$ (MPa) | Elongation to fracture (%) | Elasticity modulus E (MPa) | Impact toughness (-20°C) (J) |
|----------------|----------------------------------|------------------------------------------|---------------------------|---------------------------|-----------------------------|
| Weld metal/TWE-81K2-1 | 530-540                          | 601-628                                  | 22-23                     | 215955                    | 80                          |
| Weld metal/TWE-81K2-2 | 505-512                          | 590-605                                  | 26-28                     | 215955                    | 90                          |
| Parent plate     | 531                              | 595                                      | 24                        | 221519                    | 40                          |

Thanks to single-curve assumption, in the loading stage, the stress and strain for stabilized hardened material shows good correlations. Three specimens in each component set were averaged as weld metal constitutive relation, as shown in figure 4, which would be used as input data in ANSYS software by configuring material hardening model.

![Figure 4](image-url) **Figure 4.** Weld constitutive relation at various temperatures of (a) TWE-81K2-1 and (b) TWE-81K2-2.

### 4. Solidification Cracking Prediction by Modelling Methodology

Numerical method was utilized to further understand the mechanism of solidification cracking. Thanks to the high computational cost that welding procedure usually requires, a global-local approach was performed.

#### 4.1. Thermo-Mechanical Behaviour Prediction of Weld Components

FE models were calibrated by samples shown in figure 1. The thermo-mechanical FEM model was compared with thermocouples and residual stresses and gives good correlations, as detailed in the previous work [7]. It was then the boundary conditions, i.e., heat input, heat radiation and convection, and initial were confirmed. The upper surfaces of butt weld components were subjected to radiation and convection. The constant temperature boundary conditions were set at both side surfaces of two plates, i.e., $x = -50$ mm, and $x = 50$ mm. Heat transfer problem with the corresponding initial and boundary conditions was then solved.

For work hardening problem induced by welding thermal, isotropic hardening is sufficient to describe the thermal generated plasticity with once tensile-compress cycle nature. The bilinear Mises...
plasticity, shown in figure 4a, was selected to define weld metal mechanical properties. To avoid rigid body motion, nodal z-direction displacement was constrained at z=0. The technique of deactivate and reactivate elements is applied to simulate weld bead depositing process.

An essential point different from conventional thermo-mechanical welding FEM was the configuration of brittle impurities to account for the coupling of crack/impurity with its surrounds. Other than weld metal in weld joint, brittle impurity, typical as FeS, was characterized by a loss of ductility and sudden, often unexpected fracture causing an ever widening spectrum of component failures. Ashby [13] presented a model with hard coherency to analyse the deformation of alloys. John et al. [14] extended this model for plastic deformation problem of a sheareable precipitates particles strengthened alloy. This model was extended here for estimating the influence of thermal embrittlement impurity on crater solidification cracking.

To focus on the discrepant plasticity behaviour, the FeS elements were defined with mechanical properties far lower than weld metal to achieve a converged result. The full thermo–mechanical butt–joint model includes 35249 nodes and 30400 elements.

4.2. Weld Cracking Submodelling Technique
To detail the stress state around impurity, a local approach, submodelling technique in FEM, was utilized. A portion including crater of the full model was cut along longitudinal direction with a distance far enough from the free edge, satisfying the Saint Venant’s principle. Figure 5 shows schematically the location and size of the local model to be managed, in which 92996 elements and 110606 nodes are included. The meshes in longitudinal and transverse directions are five times and four times refined, respectively, together with further refined mesh around impurity.

![Figure 5. Schematically submodel and mesh cut from the full model (unit: mm).](image)

According to ANSYS Help, the values of degree–of–freedom (translational, potential, etc.) and body force (temperature) from the global model are imposed on the submodel corresponding cut boundaries. It is worth noted that there is a heterogeneous temperature field in submodel, and the mechanical performances of each material is temperature-dependent. The temperature interpolation is essential part for submodelling technique in welding problem. Temperature values in the full model were interpolated onto submodel as body loads. After the submodel boundaries were loaded by degree–of–freedom, body force loads and constrains, the submodel mechanical behaviour can be solved by elasto–plastic FEM.

4.3. Submodelling Technique Validation
The submodelling was validated experimentally by residual stresses. The cut boundary, $BC$, was selected, as shown in figure 5. The residual longitudinal stresses of butt-joint in the full model and the submodel, together with measured stresses by strain gauges were compared in figure 6. The maximum error of residual stresses from the submodelling and experimental measurement occurs the end of plate, which may be caused by the blind-hole technique. Since the distribution of measured data is in
agreement with modelling data, the submodelling is considered to be well consistent with the full thermo-mechanical model.

![Figure 6. Stresses comparison of modelling and measurement.](image)

4.4. Weld Stress Evolution

For comparison, the Von Mises stress of crater without impurity was extracted to well understand the stress evolution during the brittle temperature range. Figure 7a and 7b shows cross-sectional stress-histories at crater, where nodes located at surface and interior layer (2 mm from and parallel to surface, as shown in figure 7c red coloured line) were emphasized. As the butt-joint cooling down, the stresses keep symmetric and gradually converge to higher values. The Von Mises stresses are in tension due to the cooling down induced thermal shrinkage. The surface stresses at weld toes are much higher than that at weld centre due to heterogeneous constrain, indicating a serious stress concentration at weld cross-section. This stress distribution is in consistent with general knowledge that the middle part of a long weld is subjected to less stress under loading conditions.

![Figure 7. Stresses evolution of weld metal (1082 °C).](image)

Figure 7c shows the stress relative level between the surface and the interior layers. The stress of interior layer takes a tendency of low at the weld middle and high at both sides, identical with that of surface layer. However, the stresses in interior layer fluctuate smoothly crossing section with a relative higher value. This result is in consistent with that the interior layer has subjected to a relatively high level and balanced constrains.

4.5. Prediction of Solidification Crack Propagation

Since the FeS found to readily gather at the centreline of crater [15], an impurity with a dimension of 0.5 mm width × 1.3 mm depth ×5 mm length was assumed, as shown in figure 8a. The elements at crater centre supposed to be impurity, and corresponding configuration were performed by
submodelling. Figure 8b and c display Von Mises stress and plastic strain crossing section \((z = 0.2925 \text{ m})\) at 1082 °C. Figure 8d shows the stress and strain distribution at this cross-sectional surface layer. There is a sudden drop of stress, from 258.2 N/mm² at weld metal matrix adjacent to impurity to 34.8 N/mm² in impurity, giving rise to interfacial back stress, which inhibits further slip in weld metal matrix, i.e., crack propagation. Simultaneously, there is a sudden increase of plastic strain, from 0.001 at weld matrix neighbour to impurity to 0.02 at impurity, resulting in slip and cracking due to thermal embrittlement nature of impurity. The large quantity plastic makes stress relief, as observed stress drop.

![Figure 8](image.png)

**Figure 8.** Submodelling of brittle impurity embedded weld metal \((z = 0.2925 \text{ m}, T = 1082^\circ\text{C}).\)

To illustrate the stress distribution along impurity length, the stresses of weld surface layer at the impurity different cross-section, i.e., middle \((z = 0.2925)\) and end \((z = 0.295)\), were compared, as shown in figure 9.

![Figure 9](image.png)

**Figure 9.** Longitudinal comparison of (a) stress, (b) plastic strain.

As shown in figure 9a, firstly, whether impurity present or not, the stress level at impurity end cross-section is smaller than that of impurity longitudinal centre one, this result is in accordance with the founding of [16], in which the conclusion that the stress level at weld crater is lower than its previously deposited counterpart was present. Secondly, the back stresses generated at middle cross-section (223.4 N/mm²) is obviously higher than that at end cross-section (108.0 N/mm²). Thirdly, as compared to impurity free case, additive stress generated by impurity at both cross-sections are observed (stress increases from 182.9 N/mm² to 237.1 N/mm² with 29.6 % higher at impurity end cross-section case, 253.9 N/mm² to 347.5N/mm² with 36.9 % higher at impurity middle cross-section case). This generation of additive stress is consistent with the stress generated by precipitates particle in static FEM analysis in Ref. [14]. The reason is that the presence of poor mechanical impurity decreases the effective loading cross-section and incompatibility plastic occurs. The plastic strain at impurity cross-section end is much smaller that at middle. The parameters of additive stress,
interfacial back stress, the Von Mises stress level, together with plastic strain suggests consistently that the impurity propagates along cross-section is more susceptible than along length direction. This propagation mode is consistent with the surface solidification cracking case in Ref. [4], in which an open mode of weld solidification cracking was presented.

5. Discussion

The ductility of weld metal and impurity size are usually argued if they are main factors to cracking resistance in modelling method. With presented submodelling methodology, it is readily to illuminate the underlying mechanism of stress redistribution and additive stress induced by brittle impurity.

5.1. Weld Metal Ductility Influence

For HSS, weld strength matching can be generally configured as over match, equal match and under match, which can be obtained by different filler material. Among three options, low strength match is experimentally believed to be a good alternative to avoid premature solidification cracking, as exhibited in table 3. The weld metal deposited by TWE-81K2-2 filler is ductile with relatively lower strength. The two strength matches shown in table 3, equal and low strength, were discussed. Also, an impurity with a size of 0.5 mm width × 1.3 mm depth × 5 mm length at weld surface centreline was assumed. In the equal and low strength match, corresponding constitutive relation is shown in figures 4a and 4b, respectively. The comparisons of cross-sectional stress distribution are exhibited in figure 10.

![Figure 10](image)

**Figure 10.** Stresses comparison of weld metal with different ductility, (a) surface layer; and (b) interior layer.

Figure 10 shows that, with impurity or not, the minimum stress keeps appearing at the weld centre part, with much lower stress in the case of low strength match. As shown in figure 10a at the case of impurity embedded at surface layer, the additive stress generated by equal strength match (from 182.9 N/mm² to 237.1 N/mm²) is 29.6 percent. However, in the low strength match case, its counterpart value (from 200.5 N/mm² to 219.8 N/mm²) is 9.6 percent. This indicates that given a 9% reduction of weld metal strength, a 29.6% stress relief of the interface can be achieved, indicating an enhancement of crack resistance. This result is consistent with the founding [17] that the strength configuration of ductile weld metal tends to more tolerance to fracture. At the same time, the back stresses are about 87.8% and 83.6% higher in the low and equal strength match cases, respectively. The parallel distributions of stresses exhibited in figure 10b show that the additive and back stress are almost identical for whatever strength matches.

Besides the adjustment of wire filler materials shown in table 3 TWE-81K2-2 case [18], a combination of Mn and Ni contents is proved to improve the weld ductility without too much loss of weld strength in the HSSs by refinement of acicular ferrite.
5.2. The Defect Location Influence
As welding thin components, the low-melting-phase is usually pushed onto weld surface. However, as welding thick components, the last solidifying part of melting pool usually gathers in the centre of weld pool due to low temperature gradient. This scenario can be modelled by an impurity embedded interior weld metal. As the impurity moves upward, the submodelling obtained Von Mises stresses are shown in figure 11.

![Figure 11. Defect position influence on stress distribution, (a) surface layer, and (b) interior layer.](image)

As compared to the surface impurity generates additive stresses at surface layer shown in figure 11a, the surface layer additive stresses generated by interior impurity are smaller and can be ignored. However, as sown in figure 11b, the interior layer back stresses are relatively higher with a value of 26.3 percent generated by the interior impurity. It can be concluded that the impurity just makes local position be susceptible to cracking.

6. Conclusions
The susceptibility of weld crater to solidification cracking and its underlying mechanism in high strength steel welded butt-joint were investigated by experiment and modelling. Submodelling technique based FEM methodology is presented to detail impurity-type crack behaviour during thermo-mechanical welding. The main conclusions are as below:

The present FeS-type thermal embrittlement phase gives rise to a sudden drop of stress and increase of plastic strain at current weld cross-sectional layer, which generates additive stress and back stress at weld matrix-impurity interfaces, aggregating the solidification cracking. As compared to relatively small value of plastic strain at impurity longitudinal end, large quantity plastic strain occurs in the longitudinal centre of impurity indicating crack propagates readily crossing section other than along impurity longitudinal tip.

The impurity generated additive stress is position–dependent. As impurity appears at weld surface, higher additive stress and back stress are generated, exposing the impurity to be more susceptible to propagation. The additive stress is also proved to be dependent on ductility. Given a 9 percent increase of weld metal ductility, approximately 29.6 percent stress relief is observed. It is then confirmed that the improvement of weld metal ductility is an effective strategy to avoid solidification cracking.

The influence comparison of interior impurity on cross–sectional interior and surface layer shows that the impurity aggregates solidification cracking of the field near to impurity other than that of far field.

Acknowledgments
This work was supported by the Fujian Province Natural Science Foundation [grant number 2017J01485].
References

[1] Brozda J, Zeman M and Lomozki M 2000 The weldability of thermomechanically rolled S460ML steel Weld Int 14 593-605
[2] Kou S 2003 Solidification and liquation cracking issues in welding JOM 55 37-42
[3] Aucott L, Huang D and Dong H B 2017 Initiation and growth kinetics of solidification cracking during welding of steel Scientific Reports 7 40255
[4] Lei Z L, Li B W and Ni L H 2017 Mechanism of the crack formation and suppression in laser-MAG hybrid welded 30CrMnSiA joints J. Mater. Process. Tech. 239 187-94
[5] Kuo T Y, Lee H T and Tu C C 2003 Evaluation of effects of niobium and manganese addition on nickel base weldments Sci Technol Weld Joi. 8 39-48
[6] Ueda Y and Yamakawa T 1971 Analysis of thermal elastic-plastic stresses and strain during welding by finite element method Trans. Jpn. Weld. Soc. 2 90-100
[7] Chen Z L, Xiong Y F, Qiu H J, Lin G Z and Li Z M 2018 Stress intensity factor-based prediction of solidification crack growth during welding of high strength steel J Mater Process Tech. 252 270-278
[8] Bonifaz E A 2013 Submodeling simulations in fusion welds: Part II J. Multiscale Modelling 5
[9] Ye X, Hua X M and Wang M 2015 Controlling hot cracking in Ni-based Inconel-718 superalloy cast sheets during tungsten inert gas welding J. Mater. Process. Tech. 222 381-90
[10] Li Y N, Yan J C and Guo F 2014 Formation process of hot cracking in copper He shielding gas tungsten welding Trans. China weld. Inst. 8 43-7
[11] Hu B and Richardson L M 2006 Mechanism and possible solution for transverse solidification cracking in laser welding of high strength aluminum alloys Mater. Sci. Eng. A 429 287-294
[12] An, G B, Ohata M, Part J U and Toyoda M 2006 Sci Technol Weld Joi. 11 75-81
[13] Ashby M F 1970 The deformation of plastically non-homogeneous materials Philos. Mag. 21 399-424
[14] John R D, Gioacchino F D, Lim H, Edwards T E J, Schwalbe C, Battaile C C and Clegg W J 2018 Reduced partitioning of plastic strain for strong and yet ductile precipitate-strengthened alloys Scientific Reports 8
[15] Masubuchi K 1980 Analysis of welded structures Pergamon press. 18-20
[16] Wen P and Shinazaki K 2011 Experimental research and numerical simulation of solidification crack during laser welding of ring structure Acta Metallurgica Sinica. 47 1241-5
[17] Chen J W 2016 Effect of strength matching on mechanical properties of HG785 steel welded joints Hot Working Technol. 45 201-204
[18] Chen B L and Zhou Y H 1987 Improvement of toughness and strength of high strength steel submerged arc weld metal Hanjie Xuebao 8 153-161