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低 S および低 P 炭素鋼溶接金属の高温割れに関する研究
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論文内容要約

Chapter 1: Introduction

Recently, the solidification cracking was detected in the 1st and 2nd pass weld metals in the weld joint of the practical component, which was manufactured by several-passes welding with the low C filler wire to the carbon steels with different C contents. In addition, the crack was detected in the heat affected zone (HAZ) of the 1st pass weld metal by 2nd pass. It could not be identified whether the solidification cracking occurred during the 1st pass welding or the liquation cracking occurred due to the heat effect of the 2nd pass welding. However, the S and P contents of the carbon steels and the filler wire were low, and Mn content of these materials was sufficient to stabilize S as MnS. Therefore, the carbon steels and the filler wire were considered to have the low susceptibility to the hot cracking of the weld metal. Although the practical component was welded without any problems in the past, the hot cracking was detected after renewing the automatic welding machine and changing the welding conditions associated with the renewed automatic welding machine. Therefore, it was assumed that the detected hot cracking was associated with the specific welding conditions. Based on the research papers, it could not be explained why the hot cracking occurred when renewing the automatic welding machine and changing the welding conditions even though the materials had the low susceptibility to the hot cracking.

In this research, the following studies were conducted to clarify the cause of hot cracking in the weld joint of the practical component and to establish the countermeasures for the hot cracking.

(1) In order to clarify whether the hot cracking occurred in the weld metal with the low S, P and sufficient Mn contents or not when welding with the low C filler wire to the carbon steels with different C contents, the effect of travel speed on the hot cracking susceptibility of the carbon steel weld metal was studied.

(2) The effects of C content of the weld metal and travel speed on the solidification cracking susceptibility of carbon steel weld metal with the low S, P and sufficient Mn contents were studied, and the solidification cracking mechanism of the weld metal containing 0.20 wt-%C or less, low S, P and sufficient Mn contents was clarified.

(3) The effect of C content on the liquation cracking susceptibility of carbon steel weld metal with the low S, P and sufficient Mn contents was studied together with the clarification for the temperature and the plastic strain at which liquation cracking

occurs. In addition, the effect of travel speed on the plastic strain in the HAZ of 1st pass weld metal by 2nd pass was also studied in the two-passes butt welded joint, and the possibility of liquation cracking in the HAZ of carbon steel weld metal by upper pass welding was clarified.

Chapter 2: Hot Cracking Reproduction Testing by Two-Passes Butt Welding of Carbon Steels with Different C Contents

The hot cracking reproduction test was conducted using the welding mock-ups, which were made by welding with the low C filler wire (0.06 wt-%C) to the carbon steels with different C contents (0.12 and 0.34 wt-%C) most frequently used in the practical components, and the effect of travel speed on the hot cracking susceptibility of carbon steel weld metal with the low S, P and sufficient Mn contents was studied.

The solidification cracks in the 1st and 2nd pass weld beads and the crack in the HAZ of 1st pass weld metal by 2nd pass were detected. Therefore, the hot cracking can be reproduced in the carbon steel weld metal with the low S, P and sufficient Mn contents.

The C content of the weld metal increased with the increasing travel speed when the carbon steel test coupons with higher C content were welded by the low C filler wire, and the hot cracking occurred even in the carbon steel weld metal with the low S, P and sufficient Mn contents. The melting ratio of low C filler wire in the weld pool relative to the melting ratios of low/medium C base steels decreased, and the C content in the weld metal increased with the increasing travel speed. Therefore, the final solidification temperature in the solid-liquid region during the peritectic reaction decreased with the increasing C content of the weld metal due to the increasing travel speed, and the solidification cracking susceptibility increased.

The crack detected in the HAZ of 1st pass weld metal by 2nd pass is due to the solidification cracking caused by the difference in final solidification temperature in the solid-liquid region during the peritectic reaction due to the C content of the 1st pass weld metal.

Chapter 3: Effects of C Content and Travel Speed on Solidification Cracking Susceptibility of Carbon Steel Weld Metal

The test coupon and the filler wire were prepared respectively from three kinds of test materials with different C contents, and the solidification cracking testing was conducted by the welding test, where the C content of the weld metal was changed to three different C contents using the test coupons and the filler wires prepared from the same test materials together with conducting the thermal elastic-plastic analysis of the welding test to evaluate the effects of C content of the weld metal and travel speed on the solidification cracking susceptibility in the carbon steel weld metal containing 0.20 wt-%C or less, low S, P and sufficient Mn contents.

The results of the solidification cracking testing indicated that the solidification cracking susceptibility increased with the increasing C content of the weld metal and travel speed in the range of 0.14 to 0.20 wt-%C even with the low S, P and sufficient Mn contents.

A layered S enriched region at the final solidification boundary was observed from TEM-EDS analysis results. The low-melting remaining liquid film of high S concentration was present at the final solidification stage. The final solidification temperature decreases with the increasing C content, and the S is concentrated in the remaining liquid phase due to forming of the γ phase with lower equilibrium distribution coefficient of S in the solid-liquid region during the peritectic reaction. In addition, the S concentration in the remaining liquid phase further increases with the increasing cooling rate due to the increasing travel speed. Therefore, the solidification cracking susceptibility increases with the decreasing final solidification temperature even in the carbon steel weld metal with the low S and sufficient Mn contents.

The results of thermal elastic-plastic analysis showed that the plastic strain due to the solidification shrinkage of the weld metal increased with the increasing travel speed and therefore the solidification cracking susceptibility increased.

Chapter 4: Effects of C Content and Travel Speed on Possibility of Liquation Cracking in Carbon Steel Weld Metal

The high temperature tensile straining test was conducted using the carbon steel weld metals containing 0.17 to 0.21 wt-%C, low S, P and sufficient Mn contents to study the effect of C content on the liquation cracking susceptibility together with the clarification for the temperature and the plastic strain at which liquation cracking occurs. In addition, the thermal elastic-plastic analysis was also conducted to study the effect of travel speed on the plastic strain in the HAZ of 1st pass weld metal by 2nd pass in the two-passes butt welded joint.

The high temperature tensile straining testing results show that the effect of C content on the liquation cracking susceptibility was not observed in the weld metals of 0.17 to 0.21 wt-%C with the low S, P and sufficient Mn contents, and the liquation cracking susceptibility significantly increased with the increasing plastic strain when the plastic strain exceeded approximately 10 %. From the results of differential scanning calorimetry, the melting temperature of the low-melting phase present at the grain and/or dendrite boundaries in the weld metal was estimated to be approximately 1,037 to 1,118 °C.

The results of the thermal elastic-plastic analysis indicated that the plastic strain increased with the increasing welding heat input due to the decreasing travel speed in the HAZ of 1st pass weld metal by the 2nd pass. The maximum plastic strain was approximately 1.6 %, which is much smaller than the plastic strain for the liquation cracking to occur at the 1,037 to 1,118 °C even at the lowest travel speed of 20 cm/min at which the maximum plastic strain was confirmed.

It was expected that the plastic strain in HAZ of the weld metal by upper pass welding is much smaller than the plastic strain for the liquation cracking to occur in the weld joint by several-passes welding of the welded structure using the carbon steels. Therefore, the possibility of liquation cracking was very low.

Chapter 5: Conclusions

In this study, the effects of the C content of the weld metal and the travel speed on the hot cracking susceptibility were systematically studied and the hot cracking mechanism was clarified in the weld joint of the practical component, which was manufactured by several-passes welding with the low C filler wire with the low S, P and sufficient Mn contents to the carbon steels with different C contents with the low S, P and the sufficient Mn contents.

Based on the results obtained in this study, in the weld joint of the practical component manufactured by several-passes welding with the low C filler wire to the carbon steels with different C contents, it was clarified that the hot cracking susceptibility of the carbon steel weld metal increased with the increasing C content of the weld metal and the plastic strain due to the solidification shrinkage of the weld metal. Based on these results, it was clarified the conditions for the solidification cracking to occur due to the combinations of C content of the carbon steels, filler wire and travel speed, even with the carbon steels and filler wires with the low S, P and sufficient Mn contents, and therefore, this study contributes improvement of the reliability of the practical component.