論　文　の　要　旨

題　目　Evaluation and prediction method for solidification cracking during hot–wire laser welding with a narrow gap joint and GMAW process using computational simulation
（数値解析による狭開先ホットワイヤ・レーザ溶接および GMA 溶接における凝固割れの評価並びに発生予測）

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Narrow-gap welding is efficiently used to join heavy thick components. This method has the benefit of improving productivity and reducing large shrinkage. However, as a result of a narrow gap joint, the occurrence of weld metal solidification cracking is a serious problem. Currently, there are few studies regarding solidification cracking in narrow-gap welding, especially in heat resistant steel such as modified 9Cr1Mo steel, and large-scale cast steel for construction machinery. The main cause of solidification cracking susceptibility in such applications is still not clear. Based on solidification cracking theory, there are two important influences on solidification cracking; a material and a mechanical factor. The material factor is determined through the ductility of solidifying weld metal; while a mechanical factor is a high temperature weld strain developed during welding. Solidification cracking occurs in conditions where the high temperature weld strain exceeds the ductility strength of the weld metal during the solidification temperature range. Therefore, this thesis purposes to develop a method for accurate evaluation and systematic prediction of solidification cracking during narrow-gap welding employing an integrated approach between the ductility curve and the high temperature weld strain.

At first, the development of hot wire laser welding for narrow gap joints was carried out. Test pieces of ASTM A 304 stainless steel with a gap width of 3 mm were used. With welding by tentative filler rod made of Inconel 600 alloy, melting phenomena of the molten pool and the weld bead formation during welding were investigated by in-situ observation using a high-speed camera. Variations in the main welding parameters such as wire current, wire feeding position, and wire feeding angle were investigated to determine appropriate conditions. Experiments showed that under the optimum welding conditions, hot wire laser welding was able to produce complete weld deposition with very low dilution of the base metal. An experiment on laser beam reflection indicated that the laser beam reflected from the molten pool was crucial to explain the formation of the weld bead, especially in terms of melting the side groove wall of the base metal. Welding parameters, as mentioned above, significantly affected weld quality. Furthermore, in the case of welding with filler wire ER NiCrCoMo-1, the sufficiency of bonding strength at the fusion boundary was demonstrated by a tensile test, and the results showed that the metallurgical examination of the fracture surface revealed the rupture occurred at the weld metal - probably because the bonding at the fusion boundary was stronger than the weld metal. In this part, the phenomena of hot wire laser welding for a narrow gap joint and effect of welding parameters was clearly successfully.

Subsequently, hot wire laser welding with a narrow gap joint was applied to modified 9Cr1Mo steel. It was found that solidification cracking occurred in this material. The notable factors to solidification cracking susceptibility were investigated, namely the depth-to-width ratio (D/W) of a weld shape, the size of a groove width, the laser spot shape, welding with laser scanning. From the result, the effect of D/W ratio on the susceptibility to solidification cracking reveled that with a groove width of 3 mm, solidification cracking did not occur with a D/W ratio of less than 0.6 and more than 1.2. The hot wire laser welding method with a narrow gap joint was efficient for practical use because the higher D/W condition was used without solidification cracking.

Furthermore, according to solidification cracking using narrow-gap GMAW in large-scale cast steel parts with a heavy thick material for construction machineries, especially in the first weld pass of a narrow gap joint was investigated through reproducing cracking behavior by a U-groove weld cracking test. The important factors to solidification cracking susceptibility were studied such as the degree of constraint, the root gap width, and the use of different filler wires. From the results, it was found that welding by JIS Z 3312 G69A3UMN4M3 filler wire in the root gap width of 2 mm caused substantial solidification cracking. It is suggested that the wider root gap has a tendency to induce solidification cracking during welding.

In order to understand clearly the material factor of solidification cracking in narrow-gap welding, both of the modified 9Cr1Mo weld metal and the cast steel weld metal were experimented on to obtain high temperature ductility curves by means of U-type hot cracking test with an in-situ observation method. Especially, the cast steel weld metal with 40% dilution was used due to it corresponding with the actual experiments. It is found that modified 9Cr1Mo weld metal showed greater solidification cracking susceptibility than other high resistant steels such SUS 310S and Inconel 600. Meanwhile, the cast steel had lower solidification cracking susceptibility than the base metal.

The mechanical factor to solidification cracking was evaluated by a 3D-Finite element method (FEM). 3D-FEM was simulated to estimate high temperature strains in weld metal during welding. According to hot wire laser welding with a narrow gap joint, high temperature weld strain was computationally calculated in order to make clear the effect of D/W ratios on the susceptibility of solidification cracking in a theoretical theme. The special approach of welding heat source model consistent with hot wire laser welding was applied and validated based on experimental measurements. The simulation results presented that the welding heat source by hot wire laser welding was able to produce a particular weld shape at a higher D/W ratio with a lower weld strain rate. Meanwhile, FEM analysis of a U-groove weld cracking test using GMAW, welding heat source according to Goldak's model was applied. The results revealed that the inside of the weld bead induced the weld strain rate to be sharply higher than the center weld line particular in the case of 2 mm in a root gap.

Finally, the prediction of solidification cracking by comparing between high temperature ductility curve and calculated weld strain rate was analyzed. In narrow-gap welding of the modified 9Cr1Mo steel, it was found that the unique weld shape with a high D/W ratio could be achieved by hot wire laser welding. FEM results showed that the weld strain rate was very much lower than the critical strain of the ductility curve. Solidification cracking did not occur in this unique weld shape. The prediction results corresponded with the relationship between D/W ratios and solidification cracking in experiments. In narrow-gap GMAW of the cast steel using U-groove weld cracking test, FEM results revealed the calculated weld strain rate at the inside of the weld bead higher than the critical strain of the ductility curve. Solidification cracking was predicted particular in the root gap of 2 mm. The occurrence of solidification cracking agreed reasonably well with the actual experiments. The prediction approach of solidification cracking was comprehensively understood in both the material and mechanical factors in practical use.