Evaluation of Welding Residual Stress Characteristics of High-Strength Steel for Offshore Structures Based on Constraint Effect

해양구조용 고강도강의 구속도의 영향에 따른
용접잔류응력 분포 특성에 관한 연구

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Abstract

The characteristics of welding residual stress distribution in high-strength steel for offshore structures were evaluated based on the effect of constraint. It is well known that high-strength steel exhibits a high welding residual stress, and the welding residual stress is a significant factor for evaluating unstable fractures. Test specimens were manufactured by applying different constraint conditions. The constrained and unconstrained specimens were welded with the same welding consumables and conditions to evaluate the welding residual stress distribution characteristics. The cutting method was applied to assess the welding residual stresses of both specimens. The results showed that the welding residual stress at the heat-affected zone of the unconstrained specimen decreased compared with that of the constrained specimen. However, angular distortion occurred in the unconstrained specimen instead of reduced welding residual stress.

Key Words: Welding residual stress, Constraint, Offshore structure, Cutting method

1. Research Background and Purpose

As offshore energy development has been recently conducted in an extreme environment, conditions required for the installment of offshore structures have been reinforced¹⁾. Moreover, since most energy resources buried in coastal waters have been extracted, a range of energy resource mining has been extended to waters less than 1,000 m deep. Such extension of the mining range in waters has intensified environmental conditions for the installment of offshore structures²⁾, and these structures have been constantly enlarged to mine a great amount of energy. The establishment of such enlarged offshore structures requires development of high-strength steel for offshore structures and appropriate welding technology^{3,4)}. As offshore structures

tend to be built in a fixed way unlike vessels, steel for offshore structures has stricter quality requirements than that for vessels. Particularly, quality management of a welding zone is regarded as a significantly crucial parameter⁵⁾. It is essential to control welding residual stress generated in the welding process among various parameters. High strength steel shows a wide distribution of welding residual stress, which is known as a factor affecting the occurrence and spread paths of unstable fractures^{6,7)} and is significantly considered in numerous reliability tests⁸⁻¹¹⁾. It is crucial to control distortion and residual stress generated in the welding process in structures. Welding distortion affects the appearance of structures negatively and has a more negative effect on the safety of these structures. Welding residual stress must be considered to evaluate brittle fracture strength of structures^{12,13)}, and structures with a risk of fatigue

fracture should be evaluated based on welding residual stress according to components¹⁴⁻¹⁶. A distribution pattern of welding residual stress might vary according to constraints in the welding processes and structure manufacturing processes. For this reason, the optimal welding conditions should be identified to minimize welding residual stress. This study analyzed distribution properties of welding residual stress in high-strength steel for offshore structures according to the effect of constraints by adjusting welding constraints^{17,18}. To this end, this study produced and used butt joint specimens which applied different constraints. Specifically, this study evaluated distribution properties of welding residual stress by manufacturing ① a fully constrained specimen and ② a fully unconstrained specimen and welding both specimens under the same conditions. The cutting method, which is well-known as an experimental method that shows comparatively high reliability, was used to evaluate distribution properties of welding residual stress according to the effect of constraints. Based on the experimental result, this study conducted fundamental research on analyzing different patterns of residual stress generated in both specimens from the perspective of welding mechanics.

2. Applied Steel and Experimental Method

2.1 Applied steel and specimen production

This study evaluated distribution properties of residual stress in welding zones according to the effect of constraints. In the evaluation process, it manufactured and applied butt joints, which are used the most widely for structure welding, made of high strength steel with a yield stress of 500MPa (E500) for offshore structures. Tables 1 and 2 describe the chemical and mechanical properties of the E500 high strength steel for offshore structures, which was used in this study, respectively. This type of steel shows a comparatively high yield

Table 1 Chemical composition of E500 steel (wt. %)

Material	C	Si	Mn	P	S
E500	≥0.08	≥0.2	≥1.6	≥0.01	≥0.005

Table 2 Mechanical properties of E500 steel.

Material	Yield stress (MPa)	Tensile stress (MPa)	Elongation (%)	Charpy impact test, -40°C, (J)
E500	529	646	19	249J

strength of 529 MPa compared to other types of steel used for offshore structures. It also shows the average impact toughness of 249 J at -40 °C, thereby exhibiting excellent performance for impact toughness at low temperature. Mechanical behaviors in the welding zone vary depending on the effect of constraints. In this regard, this study assumed that welding residual stress and distortion will show different behaviors according to the effect of constraints. Thus, this study represented fully constrained and unconstrained conditions in experiments and investigated these conditions on residual stress and angular distortion. This study produced specimens by using a commercial AWS A5.29 E91T1 welding material, which is generally used in E500 steel for offshore structures. Tables 3 and 4 indicate the chemical and mechanical properties of the welding material respectively. The welding material produced based on overmatching joints showed the yield strength of 580 MPa, which was higher by approx. 50 MPa than that of the base metal. The tensile strength and elongation of the welding material were 650 MPa and 20% respectively. Fig. 1 shows the shape and size of specimens manufactured. Specifically, the specimens were made of 25 mm thick steel and applied the following conditions: the root gap of 4 mm and the V-groove shape which has 45° groove angle and welding length was 400 mm. The entire fully constrained and unconstrained specimens were produced under the same welding conditions, which are indicated in Table 5.

Table 3 Chemical composition of welding consumable (AWS A5.29 E91T1) (wt,%)

Welding consumable	C	Si	Mn	P	S
AWS A5.29 E91T1	0.06	0.29	1.23	0.007	0.008

Table 4 Mechanical properties of welding consumable (AWS A5.29 E91T1)

Welding consumable	Yield stress (MPa)	Tensile stress (MPa)	Elongation (%)
AWS A5.29 E91T1	580	650	20

Fig. 1 Groove shape and dimensions of test specimen

Table 5 Welding conditions in used

Process	Pass No.	Current (A)	Voltage (V)	Speed (cm/min)	Heat input (KJ/cm)
FCAW	11	270	30	32	15

* Welding Position : 1G, * Wire diameter : Φ 1.2,
* Shielding gas : 100% CO₂

2.2 Welding residual stress measurement method

Destructive or non-destructive methods are generally utilized to analyze welding residual stress. This study measured welding residual stress by using the cutting method, which is known as a destructive method that shows high data reliability. Single- and two-axis strain gauges were used in the cutting method, and a distortion rate was sequentially measured based on five densely spaced single-axis strain gauges. Table 6 presents information on the strain gauges used. Fig. 2 shows the constraints and macro sections of the fully constrained and unconstrained specimens. As for the fully constrained specimen, end tabs in the same size as that of specimens were used to fully constrain both ends of the welding start and finish sections. A steel

Table 6 2 Axis and uniaxial 5-elements strain gauge information in used

Gauge type	Gauge L	Gauge W	Backing L	Backing W	Resistance
Axis (FCA-1)	1mm	0.7mm	Φ4.5	Φ4.5	120Ω
Uniaxial-5elements	1mm	1.4mm	12mm	4mm	120Ω

backing agent was applied, and a jig was utilized in the welding process to implement the fully constrained conditions. As for the fully unconstrained specimen, both ends of this specimen were tack-welded with end tabs in the minimum size, which facilitated welding, to satisfy the minimum constrain conditions. A ceramic backing agent was applied to allow welding processes in conditions as free as possible. Fig. 3 shows the cutting location and the attachment location for strain gauges for residual stress measurement at welding zones. The distribution of welding residual stress tends to rapidly change near welding zones including heat-affected zone (HAZ). For this reason, strain gauges were densely attached near the HAZ. When residual stress is measured based on the cutting method, it is required to control the heat generated by cutting velocity. The cutting velocity was maintained as 2 mm/min, and cutting fluid and water were used to control the heat generated in the cutting process. Strain gauges were attached near

Fig. 3 Strain gauges attachment position of specimen weld

Fig. 2 Constraint condition and macrostructures of specimens

Fig. 4 Cutting process for measurement of welding residual stress with constrained and unconstrained weld

the area located at 150 mm, the center in the direction of a welding line. In the HAZ which showed considerable stress change, single-axis 5-elements strain gauges were densely attached from the direction of the fusion line to the width direction of the welding line up to the area located at 20 mm. Two-axis strain gauges were attached at the locations at 25 mm, 30 mm, 40 mm, 65 mm, 85 mm, and 130 mm, respectively, from the direction of the fusion line to the width direction of the welding line. Moreover, strain gauges were attached at the same location on the opposite surface in the direction of the welding line to ensure the reliability of distortion rates measured. Fig. 4 shows the photos of specimens taken after they were cut in the vertical direction to the welding line. The specimens were cut in the direction of the welding line and the direction of thickness to release both residual stress in the vertical direction to the welding line and welding residual stresses in the thickness direction. Cutting was conducted in directions including the thickness direction to obtain only the effect on the surface as much as possible.

3. Results and Considerations

3.1 Results of welding residual stress measured based on the cutting method

This study measured welding residual stress at weld metal zone and HAZ by applying the cutting method to

(a) Longitudinal residual stress, σ_x

(b) Transverse residual stress, σ_y

Fig. 5 Weld residual stress by cutting method

analyze the distribution of welding residual stress according to the effect of constraints. Fig. 5(a) shows distribution behaviors in the direction of the welding line. The fully constrained specimen showed tensile residual stress of 379 MPa at weld metal zones and that of 332 MPa at the location of FL+1mm. Tensile stress decreased as the measured part was far from the welding line. The fully constrained specimen showed the typical residual stress distribution of butt joints, which showed compressive residual stress of -106 MPa. In addition, the fully unconstrained specimen showed similar residual stress of 375 MPa at the weld metal zone to that of the fully constrained specimen at the weld metal zone. This result indicated that different external constraints of both specimens did not have a significant constraint effect on welding residual stress at weld metal zones. Moreover, the fully unconstrained specimen showed tensile residual stress of 202 MPa at the location of FL+1mm. Tensile stress decreased as the measured part was far from the welding line. Compressive residual stress of -9 MPa was observed at the location of FL+100mm. The fully unconstrained specimen showed a difference of residual stress of approx. 100

MPa at the same location of FL+1mm from the fully constrained specimen. The fully constrained specimen with significant constraints showed significant welding residual stress at the HAZ. However, as the measured location was moved to the base metal from the HAZ, both specimens showed a similar distribution of welding residual stress. This result was obtained because residual stress was analyzed as stress distributed at the location of base metal rather than residual stress caused by weld heat. Fig. 5(b) shows distribution behaviors of residual stress in the vertical direction to the welding line. The fully constrained specimen showed tensile residual stress of 170 MPa at the weld metal zones and that of 114 MPa at the location of FL+1mm. Tensile stress decreased as the measured part was far from the welding line. The tensile residual stress was measured as 22 MPa at the location of FL+130mm. The fully unconstrained specimen showed tensile residual stress of 135 MPa at the weld metal zones, that of 114 MPa at the location of FL+1mm, and that of 22 MPa at the location of FL+130mm. It showed similar residual stress at the weld metal zones to that of the fully constrained specimen in the direction of the welding line. The fully constrained specimen showed higher tensile residual stress at the HAZ than the fully unconstrained specimen. Furthermore, both specimens showed similar distribution tendencies of welding residual stress. Welding residual stresses were affected by contraction and expansion at welding zones including weld metal zone and HAZ according to the degree of external constraint. When external constraint was applied severely, the measured parts were constrained by contraction and expansion caused by weld heat. As a result, residual stress at the welding zone increased. On the other hand, areas located far from the welding zone were not affected by weld heat or external constraint. Consequently, residual stress was similar in these areas regardless of the effect of constraints.

3.2 A relationship between welding residual stress and distortion according to the effect of constraints

The HAZ showed a greater difference of welding residual stress distribution according to the effect of constraints than the weld metal zone, and the fully unconstrained specimen showed less welding residual stress than the fully constrained specimen. It was found that both specimens showed different welding residual stress according to the effect of constraints under the conditions where the same steel and welding requirements were applied. Accordingly, it was analyzed that welding residual stress reduced in the fully unconstrained specimen appeared in a different form. For this

Fig. 6 Angular distortion measurement of unconstrained weld

reason, this study measured the amount of distortion in both specimens. Generally, both amounts of in-plane and out-of-plane distortion should be considered. However, this study considered only angular distortion, which is out-of-plane distortion. In the fully constrained specimen, angular distortion did not occur at all due to the effect of constraints. On the other hand, angular distortion of approx. 6° occurred in the fully unconstrained specimen, as shown in Fig. 6. In other words, as the fully unconstrained specimen was not externally constrained, it accompanied free contraction, expansion, and angular distortion caused by weld heat. However, this specimen showed significant welding residual stress at the weld metal zone and the HAZ due to the effect of internal constraints. Yet, the residual stress at the welding zone was reduced in this specimen compared to that in the fully constrained specimen. It was analyzed that the reduced residual stress at the welding zone might appear in the form of in-plane or out-of-plane distortion. This study quantitatively measured only out-of-plane distortion, and it is analyzed that the reduced residual stress energy might have appeared in the form of in-plane distortion as well. This study considered only out-of-plane distortion without in-plane distortion.

4. Conclusions

This study analyzed the distribution of welding residual stress according to the effect of external constraints. To this end, it manufactured fully constrained and unconstrained specimens by using high-strength steel for offshore structures, which was 25 mm thick, and compared distribution properties of welding residual stress of these specimens. Based on the analytic results, it derived the following conclusions.

1) Both fully constrained and unconstrained specimens showed similar residual stress at weld metal zones in the direction of a welding line, which was at a similar level to the yield stress of the base metal. Moreover, both specimens showed similar distribution patterns of welding residual stress to those observed at the existing butt joints.

2) The fully unconstrained specimen showed a distribution of reduced welding residual stress at the HAZ than the fully unconstrained specimen. Both specimens showed similar welding residual stress at base metal

zones, which were unlikely to be affected by weld heat.

3) The fully constrained specimen showed a distribution of reduced welding residual stress at the HAZ according to the effect of constraints, which was observed in the form of in-plane and out-of-plane distortion.

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해양구조용 고강도강의 구속도의 영향에 따른 용접잔류응력 분포 특성에 관한 연구

Evaluation of Welding Residual Stress Characteristics of High-Strength Steel for Offshore Structures Based on Constraint Effect

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1. 연구배경 및 목적

최근 해저에너지 개발 환경이 극한 환경으로 이동함에 따라 해양구조물의 설치에 필요한 조건들이 강화되고 있다¹⁾. 또한, 근해에 매장된 에너지자원은 대부분 채굴이 완료되어서 약 1000m이하의 심해로 확대됨에 따라 해양구조물의 설치 환경은 더욱 열악해지고 있으며²⁾, 한번에 많은 양의 에너지를 채굴하기 위하여 해양구조물의 대형화가 진행되고 있다. 이러한 대형화되고 있는 해양구조물을 사용 환경에 설치하기 위해서는 해양구조용 고강도강의 개발과 적합한 용접기술의 개발이 필요하다³⁻⁴⁾. 해양구조용강재는 설치환경이 선박과 달라서 대부분 고정식으로 되어 있기 때문에 보다 엄격한 품질이 요구되며, 용접부의 품질관리는 무척 중요한 파라메타이다⁵⁾. 여러가지 파라메타중에서 용접시 발생하는 용접잔류응력의 제어는 무척 중요하다. 고강도강일수록 용접잔류응력이 크게 분포하는 것으로 잘 알려져 있으며, 용접잔류응력은 불안전파괴의 발생 및 전파경로에 영향을 미치고^{6,7)}, 각종 신뢰성 평가에 중요한 인자로 알려져 있다⁸⁻¹¹⁾. 구조물에서 용접 시 발생하는 변형과 잔류응력의 제어는 무척 중요하다. 용접변형은 구조물의 미관에도 영향을 주고 안전성에는 더욱 큰 영향을 미치게 된다. 한편, 용접잔류응력은 구조물의 취성파괴강도 평가 시 필수적으로 고려되어야 하며^{12,13)}, 피로파괴의 위험성을 갖는 구조물에 대해서는 용접잔류응력의 성분별 평가도 중요하다¹⁴⁻¹⁶⁾. 용접잔류응력은 용접프로세스 및 구조물의 제작과정에서 구속하는 방법에 따라서 그 분포양상이 달라질 가능성이 있어서, 용접잔류응력의 생성을 최소화하기 위한 최적의 용접조건을 도출을 필요로 한다. 본 연구에서는 해양구조용 고강도강을 대상으로 용접 시 구속조건을 변화시켜서 구

속도의 영향에 따른 용접잔류응력 분포 특성을 파악하기 위하여^{17,18)}, 맞대기 이음부 제작 시 서로 다른 구속조건을 적용하여 시험편을 제작하였다. ① 용접 시험편을 완전하게 구속시킨 완전구속시험편과 ② 전혀 구속을 하지 않은 완전비구속시험편을 제작하여 동일한 방법으로 용접을 실시하여 용접잔류응력분포 특성을 평가하였다. 용접잔류응력의 평가는 비교적 신뢰성이 높다고 알려진 실험적인 방법인 절단법을 사용하여 구속도의 영향에 따른 용접잔류응력 분포특성을 평가하였고, 두 시험편에서 발생하는 잔류응력의 차이가 용접역학적 관점에서 어떤 형태로 나타나는가에 대한 기초적인 연구를 수행하였다.

2. 적용강재 및 실험방법

2.1 적용강재 및 시험편제작

본 연구에서는 해양구조용 고강도강인 항복응력 500 MPa급(이하, E500) 강을 사용하여 구조물 용접에 가장 폭 넓게 사용되는 맞대기 이음부를 대상으로 구속도의 영향에 따른 용접부 잔류응력 분포 특성을 검토하였다. 본 연구에 사용한 해양구조용 E500 강재의 화학적 성질과 기계적 물성을 Table 1과 Table 2에 나타냈다. 항복강도가 529MPa정도로써 해양구조물에 적용되는 강재 중 항복강도가 높은 강재이며, 충격인성 또한 -40℃에서 평균 249J로 저온 충격인성이 우수한 성능을 갖고 있다. 구속상태의 영향에 따른 용접부에서

Table 1 Chemical composition of E500 steel

(wt. %)

Material	C	Si	Mn	P	S
E500	≥0.08	≥0.2	≥1.6	≥0.01	≥0.005

Table 2 Mechanical properties of E500 steel.

Material	Yield stress (MPa)	Tensile stress (MPa)	Elongation (%)	Charpy impact test, -40 °C, (J)
E500	529	646	19	249J

의 역학적 거동은 다르게 나타나며, 특히 용접잔류응력과 변형은 구속의 영향에 따라서 다른 거동을 할 것으로 예상되어 본 연구에서는 완전구속 상태와 완전비구속 상태를 실험적으로 재현하여 잔류응력 및 각변형의 영향을 검토하였다. 시험편 제작에 사용된 용접재료는 해양구조용 E500강재에 범용적으로 사용되는 AWS A5.29 E91T1의 상용 용접재료를 적용하였다. 용접재료의 화학적 성질 및 기계적 성질은 Table 3, Table 4에 나타났다. 용접재료의 항복강도는 모재 대비 약 50MPa 정도 높은 580MPa 오버매칭 이음부로 제작되었다. 용접재료의 인장강도와 연신율은 각각 650MPa, 20%의 특성을 갖고 있다. 시험편 제작을 위한 시험편의 형상 및 사이즈는 Fig. 1에 나타냈으며, 두께 25mm 강재

Table 3 Chemical composition of welding consumable (AWS A5.29 E91T1) (wt,%)

Welding consumable	C	Si	Mn	P	S
AWS A5.29 E91T1	0.06	0.29	1.23	0.007	0.008

Table 4 Mechanical properties of welding consumable (AWS A5.29 E91T1)

Welding consumable	Yield stress (MPa)	Tensile stress (MPa)	Elongation (%)
AWS A5.29 E91T1	580	650	20

Fig. 1 Groove shape and dimensions of test specimen**Table 5** Welding conditions in used

Process	Pass No.	Current (A)	Voltage (V)	Speed (cm/min)	Heat input (KJ/cm)
FCAW	11	270	30	32	15

* Welding Position : 1G, * Wire diameter : Φ 1.2,

* Shielding gas : 100% CO₂

를 사용하여, 용접길이 400mm, 폭 150mm에 대하여 V-groove 개선행상으로 양면 45°개선향각을 적용하여 루트갭 4mm 조건으로 시험편을 제작하였다. 용접조건은 Table 5에서와 같이 완전구속시험편과 완전비구속 시험편 모두 동일한 조건으로 제작되었다.

2.2 용접잔류응력 측정법

일반적으로 용접잔류응력의 검토에는 파괴적인방법과 비파괴적인방법이 적용되는데, 본 연구에서는 데이터의 신뢰성이 높다고 알려진 파괴적인 방법인 절단법을 이용하여 용접잔류응력을 측정하였다. 절단법에는 1축 및 2축 스트레인게이지를 사용하였으며, 5개의 촘촘한 1축게이지를 통하여 연속적으로 변형률을 측정하였다. 스트레인게이지의 정보는 Table 6에 나타났다.

Fig. 2는 완전구속과 완전비구속 시험편의 구속조건

Fig. 2 Constraint condition and macrostructures of specimens

본 논문은 독자의 이해를 돕기위하여 영문논문을 국문으로 번역하여 게재한 논문입니다. 저자는 본 논문으로 연구업적과 같은 실적에 중복으로 지원받거나 인정받을 수 없음을 알려드립니다.

과 마크로 단면을 나타냈다. 완전구속시험편은 용접 시 단부와 종단부에 시험편과 동일한 크기의 앤드탭으로 양 끝단에 완전구속을 하였으며, 스틸백킹재를 사용하였고, 용접중에는 지그를 사용하여 완전 구속시킨 상태에서 용접을 실시하였다. 완전비구속시험편은 용접이 가능한 크기로 최소크기의 앤드탭을 양 끝단에 가용접을 통하여 최소한의 구속을 하였다. 세라믹백킹재를 적용하여 최대한 자유로운 상태에서 용접을 수행하였다. Fig. 3은 용접부의 잔류응력 측정을 위한 절단위치와 스트레인게이지 부착위치를 나타냈다. 용접잔류응력 분포는 주로 열영향부(HAZ: Heat affected zone)를 포함한 용접부근방에서 급격한 변화를 갖게 되므로 최대한 HAZ 근방에 스트레인게이지를 촘촘하게 부착하였다. 절단법에 의한 잔류응력 측정 시 절단속도에 의해서 발생하는 열의 제어가 필요하다. 절단속도는 2mm/min 으로 유지하였으며, 절삭유와 물을 통하여 절단 시 발생하는 열을 제어하였다. 스트레인게이지는 용접선방향의 중심인 150mm 근방에 부착하였다. 응력변화가 심하게 발생하는 HAZ 영역은 1축 5-elements 스트레인게이지를 fusion line으로부터 용접선 폭방향으로 20mm 까지 촘촘하게 부착하였다. 2축 스트레인게이지는 fusion line에서 용접선 폭방향으로 25mm, 30mm, 40mm, 65mm, 85mm, 130mm 위치에 부착하였다. 또한, 용

Table 6 2 Axis and uniaxial 5-elements strain gauge information in used

Gauge type	Gauge L	Gauge W	Backing L	Backing W	Resistance
Axis (FCA-1)	1mm	0.7mm	Φ4.5	Φ4.5	120Ω
Uniaxial-5elements	1mm	1.4mm	12mm	4mm	120Ω

Fig. 3 Strain gauges attachment position of specimen weld

Fig. 4 Cutting process for measurement of welding residual stress with constrained and unconstrained weld

접선방향의 반대면에도 동일한 위치에 스트레인게이지를 부착하여 측정된 변형률값의 신뢰성을 확보하고자 하였다. Fig. 4에서는 용접선 수직 방향으로 절단한 후의 시험편 사진을 나타냈으며, 용접선방향과 두께방향으로 절단을 통한 용접선수직방향의 잔류응력과 두께방향의 용접잔류응력을 모두 해방시켰다. 가능한 표면에서의 효과만을 얻기 위하여 두께방향으로까지 절단을 수행하였다.

3. 결과 및 고찰

3.1 절단법에 의한 용접잔류응력 측정 결과

구속도의 영향에 따른 용접잔류응력 분포를 검토하기 위하여 절단법에 의하여 용접금속 및 HAZ에 대한 용접잔류응력 분포를 계측하였다. Fig. 5 (a)에는 용접선방향 분포 거동을 나타냈다. 완전구속시험편 용접금속에서 379MPa의 인장잔류응력이 분포하였고, FL+1mm 부분에서 332MPa의 인장잔류응력이 분포하였으며, 용접선에서 멀어질수록 인장응력이 감소하여 FL+130mm 부분에서는 -106MPa 압축잔류응력이 분포하는 전형적인 맞대기 이음부의 잔류응력분포를 나타냈다. 한편, 완전비구속시험편의 용접금속에서는 375MPa로 완전구속시험편이 용접금속과 유사한 값을 나타냈

Fig. 5 Weld residual stress by cutting method

다. 외적구속에서는 차이가 있으나, 시험편자체의 구속 효과에 의해서 용접금속의 용접잔류응력에는 큰 차이가 없는 것으로 판단된다. FL+1mm에서 202MPa의 인장잔류응력이 분포하였으며, 용접선에서 멀어질수록 인장응력이 감소하여, FL+100mm에서 -9MPa의 압축 잔류응력이 분포하였다. 완전구속시험편의 경우와 비교하면 동일한 FL+1mm에서 약 100MPa 정도의 차이가 있으며, 구속도가 큰 완전구속의 경우는 HAZ에서 비교적 용접잔류응력이 크게 나타나는 것으로 확인되었다. 하지만, HAZ에서 모재쪽으로 이동하면 두 시험편에 대한 용접잔류응력은 거의 유사한 분포를 보였다. 용접열에 의한 잔류응력 보다는 모재 부분에 분포하고 있는 응력으로 판단되어서 유사한 값을 나타낸 것으로 생각된다. (b)에는 용접선수직방향 잔류응력 분포거동을 나타냈다. 완전구속시험편 용접금속에 170MPa 인장잔류응력이 분포하였다. FL+1mm에 114MPa 인장잔류응력이 분포하였으며, 용접선에서 멀어질수록 인장응력이 감소하여 FL+130mm 부분에서 22MPa 인장잔류응력이 분포하였다. 완전비구속시험편 용접금속에

는 135MPa의 인장잔류응력이 분포하였고, FL+1mm에는 114MPa의 인장잔류응력이 분포하였으며, FL+130mm에는 22MPa의 인장잔류응력이 분포하였다. 용접선방향 잔류응력과 동일하게 용접금속에서는 거의 유사한 응력값을 나타냈고, HAZ에서는 완전구속시험편의 경우가 높은 인장잔류응력이 분포하는 것으로 나타났다. 용접잔류응력의 분포경향은 두 방향 모두 유사하게 나타남을 알 수 있다. 외적구속정도에 따라서 용접금속 및 HAZ를 포함한 용접부에서는 수축과 팽창에 영향을 받게 된다. 외적구속이 강하게 작용하는 경우는 용접열에 의한 수축과 팽창에 구속을 받게 되어서 최종적으로 잔류하는 용접부의 응력은 증가하게 되고, 비교적 용접부에서 멀리 떨어져 용접열의 영향을 받지 않은 곳은 외적구속의 영향을 크게 받지 않게 되어서 구속도의 영향에 관계없이 거의 유사한 값을 나타내는 것으로 판단된다.

3.2 구속도의 영향에 따른 용접잔류응력과 변형과의 관계

구속도의 영향에 따른 용접잔류응력 분포의 차이는 용접금속 보다 HAZ에서 크게 나타났으며, 완전비구속 시험편이 다소 작은 용접잔류응력을 나타냈다. 동일한 강재와 용접조건에서 구속의 차이에 따라서 용접잔류응력이 다르게 나타난 것은 완전비구속 시험편의 감소된 용접잔류응력이 다른 형태로 나타났을 것으로 유추되어서, 두 시험편에 대한 변형량을 측정하였다. 면내변형량과 면외변형량을 고려해야 하지만, 본 연구에서는 면외변형인 각변형만을 고려하였다. 완전구속시험편의 경우는 구속의 영향으로 각변형이 전혀 발생하지 않았으나, 완전비구속시험편의 경우는 Fig. 6에서와 같이 약 6° 정도의 각변형이 발생하였다. 완전비구속시험편은 외적구속이 없기 때문에 용접열에 의해서 자유롭게 수축과 팽창 및 각변형이 발생되었다. 또한, 외적구속이 없음에도 용접잔류응력은 내적구속의 영향으로 용접금속, HAZ에서 큰 용접잔류응력이 발생하였다. 하지만, 용접부에서 완전구속시험편 보다는 감소된 잔류응력이 분포하였으며, 용접부에서 감소된 잔류응력은 면내 및 면외 변형의 변화된 형태로 나타날 것으로 판단된다. 본 연구에서는 면외변형만을 정량적으로 측정하였고, 면내

Fig. 6 Angular distortion measurement of unconstrained weld

변형의 형태로도 잔류응력의 감소된 에너지는 나타났을 것으로 판단된다. 본 시험 범위에서는 면외변형에 대하여 검토하였고, 면내변형에 대해서는 고려하지 못 하였다.

4. 결 론

본 연구에서는 외적구속도의 영향에 따른 용접잔류응력 분포를 검토하기 위하여 두께 25mm인 해양구조용 고강도강을 이용하여 완전구속시험편과 완전비구속시험편을 맞대기 이음부로 제작하여 용접잔류응력분포 특성을 비교 분석한 결과 아래와 같은 결론을 얻었다.

1) 완전구속과 완전비구속시험편 모두 용접금속에서의 용접선방향 잔류응력은 거의 유사한 값을 나타냈으며, 그 값은 모재의 항복응력 정도의 수준이었으며, 용접잔류응력 분포양상은 종래의 맞대기이음부에서 나타나는 분포와 유사 하였다.

2) HAZ에서의 용접잔류응력은 완전비구속시험편이 완전구속시험편보다 다소 감소된 응력분포를 나타냈으며, 용접열의 영향이 거의 미치지 못하는 모재에서는 두 시험편에서 유사한 용접잔류응력 값을 나타냈다.

3) 구속의 영향에 따라서HAZ의 용접잔류응력분포는 완전비구속시험편의 경우 감소하였으며, 감소된 용접잔류응력은 면내외 변형의 형태로 발생하였다.

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