Study on Residual Stress by Neutron Diffraction in SM570-TMC Welded by Flux-Cored Wires Containing Different Nickel*

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Residual stresses developed during fusion welding operations may affect the fatigue life of the steel welded structures under dynamic loading conditions. This research aimed to investigate the residual stress distribution along the fusion welded joint. Neutron diffraction was used to measure internal stresses of flux-cored arc welded SM570-TMC steel plate, which fabricated using two different types of welding wire, E71 LT H4 (containing 0.4%Ni) and E81-Ni1 (containing 1%Ni). The longitudinal, normal, and transverse directions of residual stress were measured at the welded joint along lines 3 mm and 8 mm below the top surface. Neutron diffraction results show that residual stress in the longitudinal direction was higher than both normal and transverse directions. The residual stresses of weld using welding wire containing 1%Ni seem higher than 0.4%Ni. It may correspond to the formation of hard phases in the weld metal (WM) due to increasing nickel content.

Key Words: Neutron diffraction, Residual stress, SM570-TMC, Nickel, Weld metal

1. Introduction

Failure modes of steel structures can be affected by residual stress. The formation of residual stress may initiate stress corrosion cracking, cyclic fatigue, and cracking that have a significant impact on the life of performance of engineering structures [1-4]. Therefore, it is essential to include residual stress in the assessment of the lifetime of engineering components, especially the welded steel [3,5,6]. Knowledge of residual stress resulted in a fusion welding can be considered into the design, especially in the engineering industry, where safety factors are crucial [4].

The distribution and formation of residual stresses in and around welds are essential to understanding. The welding process generally produces residual stress along the welding direction, where the maximum value is found in the WM and heat-affected zone (HAZ) [7-8]. Residual stresses occur in and around weld due to the fusion welding need attention not only to know which design loads and stresses will support crack growth but also to determine the magnitude and direction of residual stress in the welding area [9]. Many studies have reported that fatigue cracks begin in and around welds [8]. Residual stress affects weld life because of its effect on crack growth [5,7,9].

Residual stresses that develop in the welding zone are the thermal stress. Stress is caused by strains that occur in the weld area as a result of austenite-ferrite transformation. This transformation is a complex metallurgical process in the weld joint, such as shrinkage, cooling, or phase transformation, producing tension, and compressive residual stresses in various zones of welded structures [1]. Residual stress that forms in welded structures is caused by contractions that occur during solidification when the temperature changes from the melting point of the material to ambient temperature [3,8,10,11].

Residual stress in welded structures develops in and around welds due to the temperature gradient between WM, HAZ, and base metal (BM) during welding and cooling [8,10]. The increasing temperature during welding generates an expansion of local volume in the fusion zone, which is limited by the surrounding cooler. It resulted in thermal stresses, which can produce yielding [8].

In this work, two welded plates fabricated with under matched welding wire (E71 LT H4) and matched welding wire (E81-Ni), containing 0.4%Ni and 1%Ni, respectively. The objective of this research is to investigate residual stresses along the SM570-TMC welded joint with a welding wire containing different Ni.

2. Experimental procedure

2.1 Material and welding experiment

This experiment was using SM570-TMC steel, which widely used for tall buildings and bridges, including elevated toll roads. Two identical plates, 370 mm × 150 mm × 16 mm with a single V-groove butt joint was designed for the experiment, and the welding direction was perpendicular to rolling direction (Fig.1). Welding experiment was performed on the two sets of samples, namely,
Ni04 and Ni10, using E71 LT H4 (0.4%Ni) and E81-Ni1 (1%Ni) welding wires, respectively. Those wires correspond with a tensile strength thatunder matched and matched to strength of parent material SM570-TMC. Two weld tabs were attached on both ends of the welded plate for restraint. Multi-pass welds were performed by flux-cored arc welding (FCAW) at a constant voltage 30V, current 189–199A, welding speed is varying and resulting average heat input of 0.9 kJ/mm, without preheating. The CO₂ gas was selected as shielding gas.

![Fig.1 The welded plate depicts two weld tabs for restraint](image)

The chemical composition of the material is presented in Table 1. The SM570-TMC steel was analyzed by using optical emission spectroscopy, while the manufacturer gave the chemical composition of welding wire.

### Table 1 Chemical composition of the present SM570-TMC steel and welding wires (wt%)

| Material     | C    | Mn   | P    | S    | Si   | Ni   | Cr   | Mo   | V   |
|--------------|------|------|------|------|------|------|------|------|-----|
| SM570-TMC    | 0.156| 1.469| 0.010| 0.0024| 0.517| 0.01 | 0.02 | -    | 0.005|
| E71 LT H4    | 0.02-0.06| 1.0 - 1.5 | 0.025 max| 0.025 max| 0.30 - 0.50 | 0.35 - 0.5 | 0.2 max | 0.2 max | 0.08 max|
| E81-Ni1      | 0.04 | 1.3  | 0.012| 0.01 | 0.25 | 0.92 | 0.03 | 0.003| -   |

### Table 2 Mechanical properties of the existing SM570-TMC and welding wire

| Material     | Tensile strength (N/mm²) | Yield strength (N/mm²) | Elongation (%) | Charpy V-notch J @ °C |
|--------------|--------------------------|------------------------|----------------|------------------------|
| SM570-TMC    | 590                      | 488                    | 38             | 201 @ -20 °C          |
| E71 LT H4    | 513                      | 444                    | 33             | 81 @ -30 °C           |
| E81-Ni1      | 605                      | 525                    | 27             | 120 @ -40 °C          |

2.2 Hardness tests and microstructure observation

Vickers hardness test was performed along the welded joint to characterize the hardness profile of BM, HAZ, and WM. 15 indentation points were taken at mid-depth. Hardness test was conducted using an indenter with a load of 0.3 kgf and an indentation time of 10 s.

The metallurgy observation was performed on the cross section of the weld joint. The microstructure of Ni04 and Ni10 were observed using an optical microscope with 500X magnification and continued to higher magnification by using a scanning electron microscope.

2.3 Determination of residual stress

Neutron diffraction measurements were performed using the diffractometer DN-1 installed at National Nuclear Energy Agency in Indonesia. The monochromator was single-crystal Si (311) with diffraction angle 2θ₀ (68°), giving a wavelength of 1.86 Å. Measurements were carried out using the αFe (211) reflection, at the detector angle 2θ (104°).

The neutron diffraction technique is utilized in measuring residual stress in the interior of components. Diffraction occurs based on Bragg’s law which is expressed as follows:

\[ nλ = 2d_{hkl} \sin θ \]

where \( n \) is an integer, \( λ \) is the neutron wavelength, \( d_{hkl} \) is the spacing between the planes of the atomic lattice characterized by Miller indices \( (hkl) \) and \( θ \) is the Bragg’s angle for a crystallographic plane.

Under applied stress (tensile or compressive), the lattice spacing changes (expands or contracts). At a constant neutron wavelength (\( λ \)), change in the lattice spacing can be detected as a shift (\( Δθ \)) in diffraction peak. The residual strain \( \varepsilon_{hkl} \) is defined as follows:

\[ \varepsilon_{hkl} = \frac{d_{hkl}(\text{strain}) - d_{hkl}(\text{stress-free})}{d_{hkl}(\text{stress-free})} \]

where \( d_{hkl}(\text{strain}) \) is the lattice spacing changes, and \( d_{hkl}(\text{stress-free}) \) is the lattice spacing of the strain-free or stress-free lattice parameter, which measured at 40 mm away from weld centerline.

The residual stresses in three directions: longitudinal (\( σ_x \)), transverse (\( σ_y \)) and normal (\( σ_z \)) can be calculated in the equations below:

\[ σ_x = \frac{E}{(1+ν)(1-2ν)} \left[ (1-ν)ε_x + ν(ε_y + ε_z) \right] \]

\[ σ_y = \frac{E}{(1+ν)(1-2ν)} \left[ (1-ν)ε_y + ν(ε_x + ε_z) \right] \]

\[ σ_z = \frac{E}{(1+ν)(1-2ν)} \left[ (1-ν)ε_z + ν(ε_x + ε_y) \right] \]
For the measurement, the incident and the diffracted beam slits gave the gauge volume of 3x3x3 mm$^3$. The residual stress measurement was made at two depths (Fig.2). The first line of measures was taken at 0, 3, 6, 9, 12, 17, 27, and 40 mm from the weld centerline at 3 mm below the top surface. Moreover, the second line was taken at 0, 3, 6, 9, and 40 mm from the weld centerline at a mid-depth. At each measuring point, the strain value in 3 orthogonal directions was measured.

Fig. 2 Measuring points of residual stresses.

2.4 Determination of the elastic modulus of the atomic lattice ($E_{hkl}$) and Poisson’s ratio ($\nu$)

A 6 mm thickness of the tensile specimen was extracted from the parent material SM570-TMC by wire-EDM. This tensile specimen was mounted on the neutron diffraction instrument (Fig.4) to measure $E_{hkl}$ and $\nu$. The tension load was applied on this specimen, elastic deformation occurs, and the lattice spacing changes. In this experiment, the strains in longitudinal ($\varepsilon_y$) and transverse ($\varepsilon_x$) direction were measured using neutron diffraction to determine the value of $\nu$. $E_{hkl}$ and $\nu$ can be determined from the following equation:

\[
E_{hkl} = \frac{\nu}{\varepsilon_{hkl}}
\]

\[
\nu = -\frac{\varepsilon_x}{\varepsilon_y}
\]

where a parameter termed, $\nu$ is defined as the ratio of the transverse strain ($\varepsilon_x$) and longitudinal strain ($\varepsilon_y$).

Based on this experiment, $E_{hkl}$ is 152 GPa, and $\nu$ is 0.29. The assumption in the present study is the value of $E_{hkl}$ and $\nu$ of the BM is the same as the WM and HAZ. The residual stress of Ni10 and Ni04 at 3 mm depth and mid-depth are presented in Figs.7-8 and Figs.9-10, respectively.

3. Result and discussion

3.1 Microstructure and hardness evaluation

The microstructure of Ni04 and Ni10 are illustrated in Fig.5. These microstructures were observed in the weld zone using an optical microscope with 500X magnification and scanning electron microscopy at higher magnification. WM of Ni04 showed Widmanstätten ferrite, and other features also appear, such as acicular ferrite (AF) and polygonal ferrite.

On the other hand, WM of Ni10 is mainly an AF. The concentration of AF in the WM of Ni10 was greater than Ni04.
It seems the higher nickel content in Ni10 was significantly contributed to the formation of the AF. The nickel acts as austenite stabilizer. Ni may reduce the transformation temperature from austenite to ferrite, and it produces more AF.

As observed by using a scanning electron microscope, WM of Ni04 indicated the formation of inclusions, while WM of Ni10 showed the presence of voids and microcracks. The microstructure characteristics are responsible for the hardness profile as well as residual stress.

The hardness profiles were plotted into diagrams where the hardness was measured at mid-depth along BM, HAZ, and WM (Fig.6). The result demonstrated that the hardness of HAZ is the highest, followed by WM and BM. In general, the hardness of the WM of Ni10 is higher than Ni04. It could be attributed to a solid solution strengthening where Ni10 has more nickel dissolved into the BCC matrix and increased the hardness.

3.2 Residual stress measurements

In general, the residual stresses of Ni04 and Ni10 in the weld zone exhibit different characteristics. Ni10 has higher residual stress than Ni04. It seems that the higher nickel content of Ni10 has increased solid solution strengthening in the WM. It corresponds to the hardness distribution profile, which confirmed that the WM of Ni10 has higher hardness than Ni04.

The residual stress distributions at 3 mm depth were measured along with three directions (normal, transverse, and longitudinal), as displayed in Figs. 7-8. The results exhibit that the longitudinal residual stresses (at the centerline) were higher than the normal and transverse directions for both Ni04 and Ni10. It may be caused by the accumulated expansion and contraction along the weld zone.

The highest residual stress of Ni10 was found on the weld centerline at all three directions, while the most elevated residual stress of Ni04 was found around HAZ. Both WM and HAZ are the rapid cooling rate zones. Fig.8 presented a peak value of Ni04 that found around HAZ at 9 mm position. It may affect of using under matched welding wire (the strength level of Ni04 is lower than BM). The filler metal strength level seems to influence the peak value in the WM and HAZ in this experiment.

The residual stresses distributions at mid-depth are presented in Figs.9-10. The longitudinal residual stresses tend to be higher than the normal and transverse directions. However, the longitudinal residual stress at mid-depth is lower than at 3 mm depth. It may attribute to the tempering effect of multi-pass welding. The longitudinal stresses were tension, while the normal and transverse were vary (tension and compressive). It may affect weld volume changes and structural integrity during solidification.

In this experiment, all longitudinal components, as presented in Figs. 7 to 10 showed tension from the weld centerline to the BM. It may cause the measuring points were not far enough from the weld centerline so that the compressive residual stresses have not observed it. On the other hand, other researchers reported the compressive residual stress in the longitudinal component was detected at the location more than 50 mm away from the weld centerline [7,14].

The longitudinal residual stresses exceed the yield strength of parent material was developed in the HAZ of Ni04 and weld centerline of Ni10 at 3 mm depth. The longitudinal residual stress in the HAZ of Ni04 found 108% of yield strength, while
longitudinal residual stress in the weld centerline of Ni10 found 111% of yield strength. It may cause rapid cooling that occurred near the top surface. The high longitudinal residual stress near the top surface may potentially initiate crack under the cyclic loading on the welded structure. The stress, which found higher than yield stress at the near top surface, also was reported in previous research [12-14]. W. Woo et al. [12] suggested higher residual stress near the top surface may be caused the accumulated thermal expansion or contraction and non-uniform plastic deformation.

4. Conclusions

The residual stresses of Ni04 and Ni10 in the longitudinal direction were higher than the normal and transverse directions. The longitudinal residual stresses near the top surface (3 mm depth) were higher than at mid-depth. The peak level of longitudinal residual stress near the top surface was found on the weld centerline Ni10 and the HAZ of Ni04.

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