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The effect of initial stress induced during the steel manufacturing process on the welding residual stress in multi-pass butt welding

Jeong-ung Park [a], Gyubaek An [b,*], Wanchuck Woo [c]

[a] Dept. of Civil Engineering, Chosun University, South Korea
[b] Dept. of Naval Architecture and Ocean Engineering, Chosun University, South Korea
[c] KAERI, Neutron Science Division, Daedeok-daero, Yuseong-gu, Daejeon, South Korea

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Abstract

A residual stress generated in the steel structure is broadly categorized into initial residual stress during manufacturing steel material, welding residual stress caused by welding, and heat treatment residual stress by heat treatment. Initial residual stresses induced during the manufacturing process is combined with welding residual stress or heat treatment residual stress, and remained as a final residual stress. Because such final residual stress affects the safety and strength of the structure, it is of utmost importance to measure or predict the magnitude of residual stress, and to apply this point on the design of the structure. In this study, the initial residual stress of steel structures having thicknesses of 25 mm and 70 mm during manufacturing was measured in order to investigate initial residual stress (hereinafter, referred to as initial stress). In addition, thermal elastic plastic FEM analysis was performed with this initial condition, and the effect of initial stress on the welding residual stress was investigated. Further, the reliability of the FE analysis result, considering the initial stress and welding residual stress for the steel structures having two thicknesses, was validated by comparing it with the measured results. In the vicinity of the weld joint, the initial stress is released and finally controlled by the weld residual stress. On the other hand, the farther away from the weld joint, the greater the influence of the initial stress. The range in which the initial stress affects the weld residual stress was not changed by the initial stress. However, in the region where the initial stress occurs in the compressive stress, the magnitude of the weld residual compressive stress varies with the compression or tension of the initial stress. The effect of initial stress on the maximum compression residual stress was far larger when initial stress was considered in case of a thickness of 25 mm with a value of 180 MPa, while in case of thickness at 70 mm, it was 200 MPa. The increase in compressive residual stress is almost the same as the initial stress. However, if initial stress was tensile, there was no significant change in the maximum compression residual stress.

Keywords: Initial stress; Thermal elastic plastic FE analysis; Welding residual stress; Manufacturing steel process; Multi-pass butt welding

1. Introduction

A residual stress generated in the steel structure is broadly categorized into initial residual stress induced during the manufacturing of steel material, welding residual stress caused by welding, and heat treatment residual stress by heat treatment after welding. Initial residual stresses induced during the manufacturing process is combined with welding residual stress or heat treatment residual stress and remains as a final residual stress. Because such final residual stress affects the safety and strength of the structure, it is crucial to measure or predict the magnitude of residual stress, and to apply this factor on the design of the structure. Therefore, the effect of the initial stress on the buckling strength, fatigue strength, and brittle fracture of the structure has been studied by several researchers as follows.

* Corresponding author.
E-mail address: gyubaekan@chosun.ac.kr (G. An).
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Initial stress which is generated during the manufacturing steel structure occurs due to a temperature difference on the surface and inner side of steel while it goes through the heating and cooling process during manufacturing. According to research results (Park et al., 2014a), it has been reported that the magnitude of initial stress during steel manufacturing occurred until almost 60% of yield stress. Such initial stress occurred mainly during the manufacturing process of TMCP steel during the initial stage, and such initial stress causes large deformation (Kim and Bae, 1991), thus the effectiveness of steel use is reduced. Dong et al. (2004) and Brust et al. (1998) were trying to quantify the effects of steel manufacturing processes on the residual stress characteristics in original plates under as-received conditions using a series of advanced computational modeling techniques. They reported that the fundamental mechanism is the release of residual stresses of the original plate during cutting, which cause plate deformation, resulting in dimensional inaccuracies in cutting and welding processes. Ueda et al. (1994) and Dean and Shoichi (2010) reported that in case of symmetric cutting, though initial stress did not affect welding deformation much, when cutting position and method were changed, the initial stress was affected much using FE analysis. Park (1997) studied the effect of the initial stress and initial deformation on the welding deformation. They reported that the shape and magnitude of the initial deformation affected welding deformation rather than initial stress, which was generated symmetrically. However, a detailed research was not executed on the relationship between initial stress and welding deformation.

In the buckling strength of the column member like H-beam, H-beam which is widely used as a column component is cooled and shrunk first at its end portion in the flange, and its middle portion was slowly cooled, thus compression stress occurred at the end, while tensile stress was generated at the middle, affecting the buckling strength. If compression load is imposed on the component having initial stress, compression residual stress reaches yield stress from the end of the flange having large compression stress, the area of yield stress is widened towards the inside of the flange, and the effective area becomes reduced as much as the original area. Such stiffness values of the effective section are different from each other based on a component's axis, and buckling stress values for the buckling axis are also different from each other. Finally, buckling stiffness (Uy, 1998; Real et al., 2004) is decreased by the effect of initial stress. Further, since the buckling strength (Chounga et al., 2014; Jeom Kee et al., 1999) of the structure, on which a stiffener was welded on the main plate, was also reduced by the effect of the welding residual stress during welding, it is necessary to calculate buckling strength. It is important to consider residual stress because buckling strength is affected not only by initial stress but also by welding residual stress.

In the fatigue aspect, stress concentration by the geometry of the welding joint and residual stress by welding affect the mean stress (Kim and Kim, 2015) while the weldment receives cycle load, finally affecting fatigue life (Fuchs and Stephens, 1980; McClung, 2007). Therefore, efforts are made in reducing the effect of stress concentration using post-treatment to improve fatigue strength on the welding toe by improving the welding bead shape. Such post-treatment includes burr grinding (Kang et al., 2006; Hansen et al., 2005), peening (Haagensen and Maddox, 2001), TIG treatment (Haagensen and Maddox, 1995, 2001), ultrasonic impact treatment (Statnikov et al., 2002; Tryfyakov et al., 1993), and friction stir processing (Park et al., 2011).

In the brittle fracture, the safety of the steel structure poses an issue as the thick weldment is increased following the large size of a structure which is intended to maximize productivity and efficiency. With the increases of ships and plant structures operating under a low-temperature environment, the brittle fracture safety of the structure becomes another important issue. An et al. (2011, 2014) performed a large scale brittle fracture test for various thicknesses in order to find out factors affecting unstable fracture by applying high-heat input welding and low-heat input welding. In addition, they investigated the effect of residual stress on the unstable fracture by measuring residual stress distribution (Luo, 1997; Park et al., 2014b) according to each welding process. They found out that crack propagation path, which was generated during unstable fracture, was largely affected by the residual stress according to heat input welding. The residual stress towards thickness particularly affected the crack propagation path greatly. Therefore, the measurement and predication of the initial and welding residual stress are highly important in order to evaluate structure safety. In order to evaluate the generation and propagation of a crack, it is important to measure not only surface residual stress but also internal residual stress. Surface residual stress can be measured by X-ray method (Birkholz et al., 2004), hole drilling method (Sicot et al., 1999), etc. while internal residual stress can be measured by neutrons (Okido et al., 1999; Woo et al., 2000), deep-hole drilling (Smith et al., 2000; Mahmoudi et al., 2009), inherent strain (Murakawa et al., 1996; Prime, 2001), and contour method (Ueda et al., 1986). In this study, neutron method was used to measure internal residual stress. The above studies were carried out on the effect of initial stress and welding residual stress on the structure. However, these studies are mixed in the initial stress and the welding residual stress, and it is unclear how the initial stress affects the welding residual stress. Therefore, it is necessary to study the effect of the initial stress on the magnitude and influence range to welding residual stress.

In this study, in order to investigate the effect of initial stress induced during the manufacturing of steel material on the welding residual stress, initial stress was measured and analyzed for steel plates having a thickness of 25 mm and 70 mm. Thermal elastic–plastic FEM analysis was performed by setting initial condition as measured initial stresses to investigate the effect of initial stress on the welding residual stress. Further, two types of initial stresses and welding residual stresses were measured using neutron method and FE results compared with measured results in order to validate the reliability of FE analysis.