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Numerical and experimental investigation of thermal field and residual stress in laser-MIG hybrid welded NV E690 steel plates

G.F. Sun[a,*], Z.D. Wang[a], Y. Lu[a], R. Zhou[b], Z.H. Ni[a], X. Gu[c], Z.G. Wang[c]

[a] School of Mechanical Engineering, Southeast University, Nanjing, Jiangsu, 211189, PR China
[b] School of Mechanical and Metallurgical Engineering, Jiangsu University of Science and Technology, Zhangjiagang, 215600, PR China
[c] Technology Center, Nantong COSCO Shipping Engineering Co. Ltd., Nantong, 226006, PR China

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ABSTRACT

A numerical simulation with sequential coupled thermal-mechanical finite element model has been performed for analyzing the temperature field, residual stresses and distortions in NV E690 weldment fabricated by hybrid laser-arc welding (HLAW). For the detailed validation of applicability of the proposed model, simulated and experimentally measured weld pool shape, residual stresses and distortions were compared. The comparison results showed that decent agreement was realized between the predicted weld pool dimension and measured weld bead geometry, suggesting the utility of the combined heat source model for predicting the transient temperature distribution during HLAW. Besides, the simulation results denoted that higher tensile stress distributed in the fusion zone and the surrounding heat affected zone. There was a qualitative agreement in terms of the numerical and experimental results of longitudinal stress and transverse stress. Additionally, the relative error of angular distortion between the experimental and numerical results was 28.18% and the absolute error value was 0.217°. In addition, increasing the heat input increased the peak temperature, residual stresses, and distortions in the weldment. Comparison of the numerical and experimental results suggested that the developed model can be effectively used to estimate welding residual stresses and distortions in hybrid welded steel plates. What is more, the effect of welding thermal cycles on microstructure evolution of the weld bead was also evaluated.

1. Introduction

High-strength-low-alloy steel is widely used in marine engineering owing to its excellent mechanical properties [1]. The NV E690 grade steel defined by Det Norske Veritas (DNV), is a newly-developed high-strength martensitic steel. NV E690 steel is important for manufacturing offshore platforms. This steel not only possesses excellent performance in comprehensive mechanical properties, but also provides economic advantages due to low consumption of costly alloy elements. Conventional fusion welding techniques, such as gas metal arc welding (GMAW) and tungsten inert gas welding (TIG), are incapable to meet the ever-growing demand of industrial production efficiency and quality. In recent years, laser beam welding technique has been widely applied in automobile industry. But this technique still meets some difficulties when it is employed to weld steel plates with large thicknesses. Compared with arc welding and laser welding, hybrid laser-arc welding (HLAW) shows great advantages in both weld quality and welding efficiency [2–4]. The HLAW has attracted special attention in many manufacturing fields including pipeline construction, aerospace, shipbuilding industries and marine equipment during recent years [5–8].

When the as-welded structures are employed in real situations, welding residual stress and distortion are the two major concerned problems. The rapid heating and cooling cycles give rise to inhomogeneous expansion and contraction of the fusion zone and adjacent base materials, resulting in the formation of residual stresses and unwanted distortions. The residual stresses in near-weld region are normally tensile stresses owing to the shrinkage of the fusion zone in the cooling process [9]. Those post-weld tensile residual stresses frequently result in brittle fracture [10] and premature failure of the weldment [11]. The reason is that the tensile residual stresses can accelerate crack growth around the weld region and enhance the rate of fatigue rupture [12]. Welding residual stresses lead to the formation of distortions. Deng et al. reported that the welding distortion has detrimental influences on the external appearance, assembly accuracy and strength of the welded structures [13]. For example, the oversize radial deformation of the welded cylindrical legs which serve as bearing structures under the sea, might contribute to the failure of engineering

* Corresponding author.
E-mail addresses: gfsun@seu.edu.cn, gfsun82@126.com (G.F. Sun).

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Nomenclature

v	Welding speed, m/min
t	Welding time, s
T_m	Melting point, °C
T	Temperature, °C
Q_v	Internal heat generation rate, W/m^3
k	Thermal conductivity, W/(m·K)
C_p	Specific heat of work piece, J/(kg·°C)
q_{arc}	Power density of arc, W/m^3
q_{laser}	Power density of the laser beam, W/m^3
P_{arc}	Arc power, W
P_{laser}	Laser power, W
I	Arc current, A
U	Arc voltage, V
η_{arc}	Arc efficiency
η_{laser}	Laser efficiency
H	Effective interactive depth, m
r_0	Opening radius of the arc heat source, m
r_h	Bottom opening radius of the arc heat source, m
k_r	Attenuation rate of the radius of the arc
$r_0^{'}$	Effective radius of the laser heat source, m
r	Current radius, m
x, y, z	Cartesian coordinates, m
T_∞	Ambient temperature, °C
$q^{''}_{conv}$	Heat loss due to convection, W/m^2
$q^{''}_{rad}$	Heat loss due to radiation, W/m^2
$q^{''}_{cond}$	Heat loss due to conduction, W/m^2
h_{conv}	Heat transfer coefficient, W/(m^2·°C)
k	Heat transfer coefficient, W/(m^2·°C)
q_t	Total surface heat transfer, W/m^2
α_t	Total heat transfer coefficient, W/(m^2·°C)
$H^{'}$	Enthalpy, J/m^3

Greek symbols

ε	Emissivity of the work piece
σ	Stefan-Boltzmann constant, W/(m^2·°C^4)
ρ	Density of the work piece, kg/m^3

Subscripts

∞	Ambient

structures, leading to enormous economic losses. Therefore, it becomes of critical importance to study the evolution mechanism of the residual stresses and distortions formed during the welding process for the reason that they can significantly influence the mechanical properties and structure performance of the weldments. Additionally, it is necessary to further estimate the mechanical behavior of the weld joint in the design phase to ensure structural integrity of a welded construction.

The welding residual stresses and distortions have been studied by experiments for years and a great deal of fundamental knowledge has been established [14,15]. Technically speaking, experimental trials to obtain acceptable results are time consuming and complex, as well as require an expensive testing cost [16]. Additionally, the results obtained by experiments are often subjected to welding equipment and welding methods, as well as specimen geometries. Because of this, the results cannot be put into use at the time when the experimental parameters are changed. Numerical analysis can be used as an efficient way to help optimize welding parameters and obtain appropriate mechanical properties involved in welding process [17,18]. Numerous researches have reported the numerical simulation of welded structures over the last decade or so. For example, Deng et al. developed a 3D model and 2D axisymmetric model to simulate the temperature residual stress fields in SUS 304 stainless steel pipe [19]. They suggested that both the models were able to be effectively used to predict the thermal and residual stress fields. Zain-ul-abdein et al. focused on the influence of metallurgical phase transformation on residual stress and distortion of laser welded aluminum alloy AA 6065-T4 [20]. Chukkan et al. carried out simulation process with three different heat-source model to predict welding deformation and residual stress in AISI 316 L stainless steel welded by laser beam [21]. Liang et al. investigated the influence of deposition pattern on welding residual stress by means of experiment and numerical simulation [22]. Kong et al. employed a finite element model including arc heat source and laser heat source to model the hybrid laser-arc welding process [23,24]. They suggested that the proposed finite element model could be further employed to the optimization of the welding parameters. Additionally, some experts simulated the heat transfer and fluid flow in laser-arc hybrid welding process [25,26]. The three-dimensional numerical model based on finite volume method was employed in their research.

In view of the above mentioned, many studies have been done so far to simulate the welding process. A large proportion of research attention has concentrated on the laser welding or arc welding. A small number of studies focus on the investigation of residual stresses and distortions accompanied with the HALW process. The numerical analyses of HLAW process were usually preformed on short specimens (less than 100 mm). A good understanding of the relationship among the welding parameters, residual stresses and distortions in long weld components, is very important for quality control and performance improvement in practice. Besides, to the best of the authors' knowledge, little work was reported about the simulation of hybrid welding of NV E690 steel and the process is far from being optimized. Therefore, this current investigation intends to establish the research on application of laser-MIG hybrid welding to the 15 mm thick steel plates using simulation method and experimental approach.

In the present research, a three-dimensional (3D) thermo-mechanical finite element model was developed to achieve high accuracy prediction of weld bead profiles, residual stresses and distortions in the weldment fabricated by HLAW. A reasonable combined heat source model was proposed to consider the specific heat input profiles caused by MIG arc heating and laser radiation. Meanwhile, the correctness of the elaborated model was validated by experiments, such as residual stresses measurements by X-ray techniques, distortions measurement by a coordinate measuring machine (CMM) and weld pool geometry measurements. What is more, microstructure evolution associated with the thermal histories in various zones, namely fusion zone (FZ), heat

Table 1
Chemical composition of NV E690 steel and filler wires MGS-88 A (wt %).

Material	Composition											
	C	Si	Mn	P	S	Cr	Mo	Ni	Al	Cu	V	Ti	Fe
NV E690	0.138	0.283	1.28	0.0185	0.0052	0.176	0.119	0.0110	0.0281	0.0148	0.0032	0.0068	Bal.
MGS-88A	0.06	0.50	1.59	0.005	0.005	–	0.78	3.56	–	0.18	–	–	Bal.