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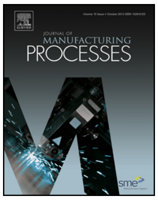

Technical Paper

Investigation of transient/residual strain and stress in dissimilar weld

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ABSTRACT

Optimizing welding parameters to achieve low residual stress (RS) with the aid of stress reduction techniques usually relies on the study of residual strain distribution in weldment. However, investigating transient strains using experimental methods such as strain gauges gives an additional view on how RS is reduced. In this work, the transient strain and stress on the surface of dissimilar plate during gas-tungsten arc (GTA) welding process have been studied using non-destructive strain gauge method. It is demonstrated that strain gauge measurements during dissimilar welding processes can be used to indicate residual elastic strain and stress. Moreover, three- dimensional (3D) finite element (FE) model has been developed and verified with experimental work (neutron diffraction measurement), and was employed to examine the formation of RS upon cooling of a 304-1018 dissimilar weldment. The strain gauge (SG) measurement method shows good agreement with FE model and neutron diffraction measurements. The assumptions and limitations associated with strain measurement and determination of the stress state are explored. Lastly, curvature due to dissimilar weld and its effects on strain measurement, which is in contrast with similar weld, was measured and discussed.

1. Introduction

Dissimilar weld provides possibilities for the flexible design of the component by using each base metal (BM) efficiently i.e., benefiting from the specific properties of each base metal to meet functional requirements. However, these joints are prone to frequent failures such as cracking at heat affected zone (HAZ) regions during service in power plants caused by residual stress (RS) [1]. Thus, it is necessary to evaluate RS in the dissimilar weldment. Presently, there are a variety of experimental methods for this purpose, such as neutron diffraction (ND), X-ray diffraction, hole drilling, and sectioning techniques [2]. In a recent study, Qiao [3] has used a new testing method to establish to quantitatively determine the residual plasticity in a dissimilar weld through micro hardness mapping. They summarized these relationships in Eq. (1).

$$HV_{304L} = 382 \times \varepsilon^{p} + 152$$

$$HV_{A600} = 457 \times \varepsilon^{p} + 175 \qquad (1)$$

However, there are limited studies that have focused on the transient strains during welding process experimentally. For instance, in the experimental study by Davoud [4], strain history was measured during gas-metal arc (GMA) similar welding process on two mild steel plates and two A-36 plates. It was demonstrated that reliable measurement of thermal and strain history during an arc welding process is possible upon recognizing sources of error resulting from the severe measurement environment. Similarly, Coules et al. measured the transient strain field caused by GMA welding of steel plate specimens [5]. They concluded that slight difference in the longitudinal stress field in surrounding material is occurred whether the weld is carried out at a butt joint interface or on single solid piece of material (bead-on-plate configuration). According to these two studies [4–6], thus it is interesting to further investigate transient strain during welding process, especially in dissimilar weld, which has received increased attention in the last two decades. In general studying strain and stress histories experimentally offers unique capabilities in various ways:

First, although numerical models deliver fundamental insight into stress formation during welding process, they usually have been corrected by residual stress collected after the weld process rather than transient stress, which occurs during process. In order to obtain the best FE model, it is suggested to validate the model not only with residual stress, but also with transient stress, which is the main motivation of this study.

Second, despite of the recent studies of transient strain and stress in similar welding [4,6,7], no previous experimental measurements in dissimilar welding have been found in the literature. More investigation needs to be geared toward monitoring and con-

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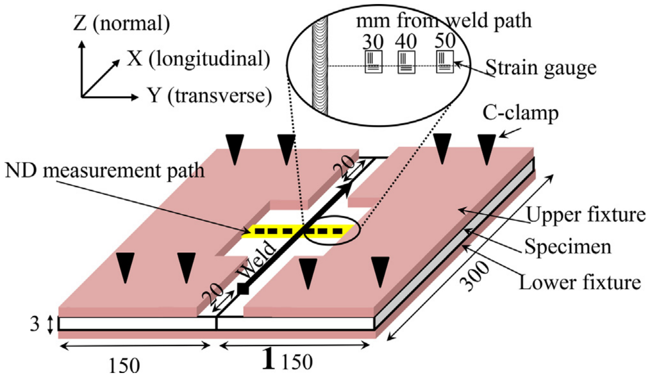

Fig. 1. Dimensions and principal directions of the specimen, dimensions are in "mm".

trol in dissimilar welding especially when coefficients of thermal expansion (CTE) of two base metals (BM) are relatively large[8].

The third drive for transient strain measurement is as a means of determining the residual strain, by considering the steady state values after cooling down to room temperature [9].

In this study, SG measurement, FE model and ND methods were used to investigate transient strain and stress in dissimilar welds. Transient strains in the longitudinal and transverse directions were recorded at the surface of weld specimens throughout experiments using strain gauge. These measured data were then compared with ND and FE results, in which good agreement were observed. The result of this study shows that the ability to take experimental measurements of the transient stress field would greatly allow verification of modeling efforts and give further insight into the development of RS in dissimilar weldment. SG technique presented in this study shows that it is a useful tool for comparative studies of weld induced RS since it is non-destructive and it can also be carried out with less specialized equipment.

2. Experiments

The experimental layout and material compositions of the alloys used in this study, are shown in Tables 1 and 2, respectively. Single pass autogenous GTA welding was used for all cases. The welding parameters (displayed in Table 2) were designed so as to produce partial penetration since no auxiliary argon gas was accommodated for weld protection underneath. The specimens were held completely flat using a C-clamps as they were welded, and were released 800 s after completion of the weld. After welding, the specimens were allowed to cool, after which time the temperature had approximately equilibrated, before being released from the C-clamps. Dimensions of samples are shown in Fig. 1.

2.1. Strain gauge measurement

Strain measurements were recorded at the upper surface of weld specimens throughout experiments. In order to measure longitudinal and transverse strains, CEA-06-062-35 and CEA-09-062-35 (Vishay Tee Rosette gauges), were used for 1018 steel and 304 stainless steel, respectively. The strain gauges (SG) were placed at 30, 40 and 50 mm away from the weld path. This is because temperature of locations closer to weld path (<25 mm) are relatively high when compared to SG temperature limits. A clamping system was used to secure the specimens for the duration of the experiment. To calculate the stress field, a purely biaxial state of stress assumption was made. SG measurements were taken from both sides of the dissimilar weld using SG arranged in a linear pattern, as shown in Fig. 1. All SG had a measurement grid length of 3.05 mm, and individual quarter-bridge circuits were used for each gauge.

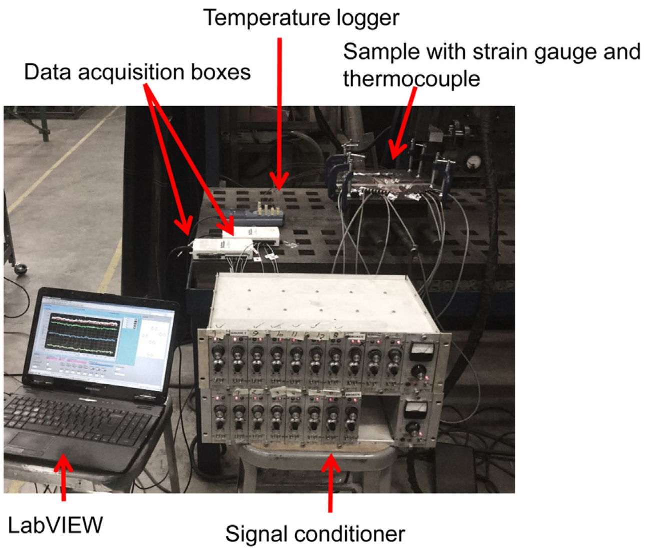

Fig. 2. Strain gauge and temperature data acquisition system.

In this study, measuring temperature was carried out as it is important in two ways. First this measurement was used for temperature compensation in order to isolate the elastic strain, which will be discussed in the *elastic strain measurement* section. For this purpose, K-type thermocouples were spot welded to the specimens at six SG locations, (three on 304 side and three on 1018 side at 30, 40, and 50 mm away from the weld center line). Second it was used as a reference for validating the numerical model, which will be detailed in the *finite element modeling* section. For this task, another set of three K-thermocouples were placed at 10, 15 and 20 mm away from the weld center line. The data acquisition was carried out using the Omega data acquisition system. The parameters to be logged and the detail sampling frequency, number of channels to be used, etc. were programmed using LabVIEW. The data acquisition system is then triggered with the thermocouples connected to the relevant terminals. The temperature data was acquired at a rate of 10 Hz. Both the thermocouples and strain gauges were protected from the radiated heat and electronic interference generated by the welding arc using glass fiber and aluminum foil shielding. As found in previous studies by Coules and Davoud [4,6], careful shielding of the instrumentation was necessary to achieve accurate measurements in the presence of the GTA weld arc. Fig. 2 shows the experimental set up used in this investigation.

2.2. Elastic strain measurement

The total strain recorded by strain gauge ($\boldsymbol{\varepsilon}^{SG}_{total}$) at any point on the specimen is the sum of strains due to temperature ($\boldsymbol{\varepsilon}^{SG}_{t/o}$), due to elastic deformation ($\boldsymbol{\varepsilon}^{SG}_{e}$), and due to plastic deformation ($\boldsymbol{\varepsilon}^{SG}_{p}$). In order to calculate longitudinal and transverse strains, it is necessary to isolate elastic deformation, see Eq. (2).

$$\boldsymbol{\varepsilon}^{SG}_{e} = \boldsymbol{\varepsilon}^{SG}_{total} - \left(\boldsymbol{\varepsilon}^{SG}_{p} + \boldsymbol{\varepsilon}^{SG}_{t/o}\right) \tag{2}$$

Three components, $\boldsymbol{\varepsilon}^{SG}_{total}$, $\boldsymbol{\varepsilon}^{SG}_{p}$ and $\boldsymbol{\varepsilon}^{SG}_{t/o}$ are needed in order solve Eq. (2). $\boldsymbol{\varepsilon}^{SG}_{total}$ is the raw data recorded by strain gauges. To compensate for the effects of temperature, $\boldsymbol{\varepsilon}^{SG}_{t/o}$ was calculated by temperature data from the thermocouples. At 30, 40, and 50 mm measurement points, it was assumed that no plastic deformation occurs during