CORRECTION OF BUTT-WELDING INDUCED DISTORTIONS BY LASER FORMING

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KEYWORDS

Welding, Distortion, Correction, Laser Forming

ABSTRACT

Welding-induced distortion is an intrinsic phenomenon arising due to the thermally induced strain distributions in the weld and surrounding material. The distortion can be minimized during the pre-process, real-time, or post-process stages. In the present paper, the laser forming (LF) technology is utilized for the post correction of welding-induced distortion. The out-of-plane distortion can be divided into angular and longitudinal distortions. The LF correction paths are based on the magnitude and direction of bending angle, and the longitudinal residual stresses. The heating conditions are determined through the use of a heating database established by FEM simulations. It is seen that laser forming can reduce not only the welding-induced distortion, but also the tensile longitudinal residual stresses on the welded surface.

INTRODUCTION

Welding induced distortion is a common problem in industrial application. The fundamental cause of the welding induced distortion is the non-uniform heating of material during the welding process, which in turn produces plastic strains and residual stress due to the strain distribution induced by thermal expansions in the weld and surrounding material. Four types of welding-induced distortion were characterized by Masubuchi (1980). The first two are in-plane longitudinal and transverse shrinkage. The other two are angular and longitudinal distortion (bowing), which appear out of plane. The angular distortion is mainly caused by the non-uniform extension and contraction through thickness direction due to the temperature gradient. The longitudinal distortion is generated by the longitudinal tensile residual stress. The distortion causes the degradation of the product performance and the increase of the manufacturing cost due to the poor fit-up, and need to be minimized to an acceptable level.

Numerous investigations have been done to remove the welding distortions and they can be classified into pre-process, in-process and post-process methods. The pre-process approaches attempt to balance the residual stress by optimizing the welding conditions (arc voltage, current, welding speed, electrode material etc.), structural design, fixture design, and welding sequence. These approaches can only reduce the welding induced distortion to certain extents, limited by the original structural and welding process design. In-process approaches, on the other hand, aim to minimize the residual stress during the welding process. Deo and Michaleris (2003) proposed a transient thermal tensioning method, which uses two heating torches along the welding path. Xu and Li (2005) proposed another dynamic thermal tensioning method which also uses multiple torches but the preheating torches are not necessarily along the welding path and the preheating strategy is optimally determined. Most of these methods provide pre-tensions through mechanical or thermal means to compensate for the welding induced strains caused by thermal expansion.

In most cases, welding-induced distortions are difficult to predict so that the pre- or in-process approaches are limited to be implemented. Instead, the post-welding straightening method can be adopted. Compared with mechanical straightening, thermal straightening is the preferred method because the material is handled considerably gently while its shape is being altered. Flame straightening was widely used from the middle of last century. However, this approach is labor intensive, inaccurate and expensive. As a more controllable and repeatable approach, laser forming provides a promising way to eliminate the welding-induced distortion. However, few investigations have been taken during the last two decades since laser forming was proposed.

Laser forming is a non-traditional manufacturing technology based on the generation of thermal strain through laser heating without hard tooling. This brings industrial promise in a wide spectrum of applications, e.g. shape tuning. Geiger et al. (1993) was the first one to apply laser forming to the straightening of car body shells. They found that post-welding distortion correction and laser induced bending are controlled by the same parameters, suggesting the use of the LF process as an effective means for the minimization of these undesirable deformations. However, only angular distortion was accounted for in their investigation.

In the present paper, characteristics of distortion and residual stress after welding are highlighted first. The features of laser forming are also presented. To remove the angular distortion, laser forming under temperature gradient mechanism (TGM) is applied along the welding path on the bottom surface. To remove the longitudinal distortion, the buckling mechanism (BM) laser forming is applied perpendicular to the welding path on the top surface by counteracting the longitudinal tensioning stress. Corresponding heating conditions can be obtained from the heating database established by FEM simulation. The proposed strategy is verified through the bead-on-plate welding on mild steel plates with three types of weld paths.

EXPERIMENTS AND SIMULATION

Experiments of Welding

In this study, bead-on-plate laser welding was carried out to investigate the welding induced distortion (shown in Fig. 1). The material investigated is cold-rolled AISI 1010 steel with dimension 80x80x0.89 mm. Before the welding, stress relief annealing is used to reduce the residual stresses due to the previous cold-rolling manufacturing process. Samples are heated to 600 ~ 625 ^{0}C. and held for 1 hour and then slowly cooled in still air. After this treatment, over 90% of the initial residual stresses are eliminated.

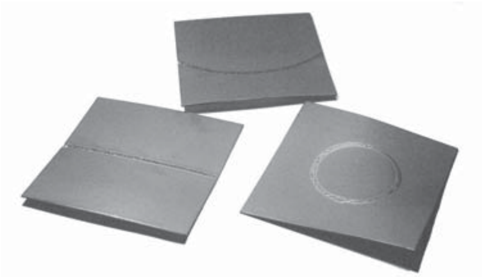

FIGURE 1. SAMPLES SHOWING THE WELDING-INDUCED DISTORTIONS

The laser system used in both the welding experiments and laser-forming (LF) correction is a PRC-1500 CO_2 laser, with a maximum output power of 1.5 kW and power density distribution of TEM_{00}. The diameter of the laser beam used in welding is 4mm, which is defined as the diameter at which the power density becomes $1/e^2$ of the maximum power value. Three types of welding paths: straight, curve and circular lines bead-on-plate welding are studied in this paper to develop more general LF correction strategies. A typical heating condition (Laser power=1200 W, welding speed=10 mm/s) was applied in the welding experiment. A coordinate measuring machine (CMM) is used to measure the induced out-of-plane distortion. Bending angle may vary along the scanning path; hence, bending angle was measured at equally spaced locations along the scanning path. To enhance laser absorption by the workpiece, a graphite coating was applied to the surface exposed to the laser.

Numerical Simulation of Welding

The welding process is a fully coupled thermal, mechanical and metallurgical process. In this study, the problem is simulated as a sequentially coupled thermo-mechanical process neglecting the effect of phase transformation. The solution procedure consists of two steps. First, a transient nonlinear heat transfer analysis is performed to determine the temperature distribution. The temperature history calculated in the heat transfer analysis is then used as a thermal load in the subsequent mechanical analysis. All the material properties are temperature dependent. Work hardening and rate-dependent flow stress is also taken into account.

In the thermal analysis, latent heat and near-melting-temperature material data are accounted for. The thermal conductivity above the melting temperatures is artificially increased to compensate for the convection heat transfer effect in the molten weld pool.

The governing equation of the thermal process in the beam is a standard transient heat conduction equation:

$$\rho c \frac{\partial T}{\partial t} = q + \frac{\partial}{\partial x}(k_x \frac{\partial T}{\partial x}) + \frac{\partial}{\partial y}(k_y \frac{\partial T}{\partial y}) + \frac{\partial}{\partial z}(k_z \frac{\partial T}{\partial z}) \tag{1}$$

where ρ is the density, c is the heat capacity of the steel, q is the heat generation rate per unit volume, $T = T(x, y, z, t)$ is the instantaneous temperature at any point in the domain, and k_x, k_y and k_z are the thermal conductivity of the material on x, y, and z directions. Since the steel plate is homogeneous, isotropic material properties $k_x = k_y = k_z$ are used in the model.

In the structural analysis, the plastic deformation of the material is assumed to obey von Mises yield criterion. The total strain is decomposed as the following:

$$\dot{\varepsilon}_{ij} = \dot{\varepsilon}_{ij}^{e} + \dot{\varepsilon}_{ij}^{p} + \dot{\varepsilon}_{ij}^{T} \tag{2}$$

where ε_{ij}^{e} is the elastic strain, $\dot{\varepsilon}_{ij}^{p}$ is the plastic strain, and ε_{ij}^{T} is the thermal strain. Plastic strains due to transformation plasticity is not considered in the model.

Residual Stress Measurement

In the welding process, the concentrated moving heat source causes large residual stresses around the welding path, especially in the heat-affected-zone (HAZ). Since the welding process is a plane stress analysis (no stresses in the thickness direction due to the free expansion), only transverse and longitudinal residual stresses are considered. To characterize the distribution of the residual stress, X-ray diffraction (XRD) is adopted to measure the residual stress in different directions.

A single stress σ_ϕ acting in some direction ϕ in the surface can be measured by two-measurement methods, which measures one of the strain along the surface normal, and one of the strain along an inclined direction (Ψ to the normal direction). The direction of the surface normal, the inclined direction Ψ and the direction of σ_ϕ are in the same plane. The measured residual stress is expressed as

$$\sigma_\phi = \frac{E}{(1+\nu)\sin^2\Psi}(\frac{\sin\theta_i}{\sin\theta_n} - 1) = K(\frac{\sin\theta_i}{\sin\theta_n} - 1) \tag{3}$$

where *E* is the Young's modulus, ν the Poisson ratio, and *K* is defined as the Stress Constant.

RESULTS AND DISCUSSIONS

Characteristics of Welding-Induced Distortion and Residual Stress

The out-of-plane welding distortion can be divided into angular distortion and longitudinal distortion, which is defined as perpendicular to and along to the welding path, respectively. The surface, on which the welding path was applied, is referred to as top surface, and the other side of sheet is referred to as bottom surface. The angular distortion is generated due to the non-uniformity of thermal expansion and contraction through the plate thickness. The longitudinal distortion is caused by the tensile residual stresses due to the moving heat source along the longitudinal direction.

Fig. 2 shows the distortion of straight-path bead-on-plate welding measured by coordinate measurement machine (CMM). Due to the geometry symmetry, only half plate is shown. The distribution of angular distortion (defined by bending angle) along the weld path is shown in Fig. 3. It is found that although the heating conditions remain constant along the path, bending angle varies due to the non-uniformity of the inherent constraint (from the surrounding material) and the temperature field. The bending angle can be calculated either by analytical models or by numerical simulation based on the applied heating conditions and material properties (Vollertsen, 1994). The required heating conditions can be determined if the bending angle is known although the solution is not unique.

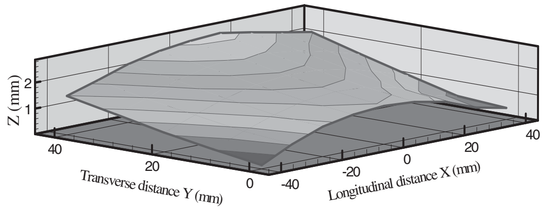

FIGURE 2. DISTORTIONS INDUCED BY STRAIGHT PATH WELDING

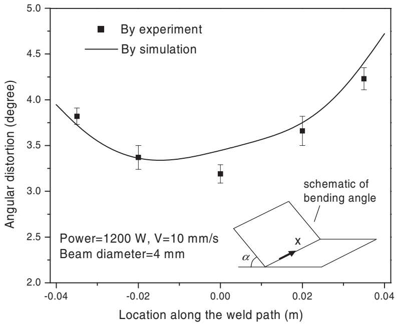

FIGURE 3. DISTRIBUTION OF ANGULAR DISTORTIONS

Since the samples are annealed to release the residual stress caused by cold rolling before welding, the residual stress measured after welding process can be assumed to be the result of welding process alone. X-ray diffraction (XRD) can be used to measure the residual stresses in any direction. The distribution of longitudinal residual stress and transverse residual stress along Y direction (the direction perpendicular to weld path) is shown in Fig. 4. Within the heat-affected-zone (HAZ or plastically deformed zone), the longitudinal residual stress on both top surface and bottom surface is tensile because of the plastic compressive deformation within the zone. It is found that the plastic compressive strain within the HAZ on bottom surface is larger than that of the top surface, so that the bending curvature along the weld path is towards the bottom surface. Outside the HAZ, only elastic strain exists. The downward curvature causes the tensile longitudinal elastic strain on the top surface, and the compressive longitudinal elastic strain on the bottom surface. So that the longitudinal residual stresses outside the HAZ are tensile on the top surface and compressive on the bottom surface.

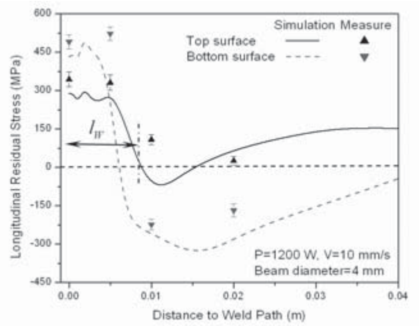

FIGURE 4. DISTRIBUTION OF LONGITUDINAL RESIDUAL STRESS

For the direction perpendicular to the weld path, it is found that within the plastic zone, the transverse residual stress is compressive on the top surface and tensile on the bottom. The reason can be explained as follows. For the welding process, due to the very low scan speed and so-caused low temperature gradient through the thickness, the compressive strains in the transverse direction occurring on both top and bottom surface within the plastic zone are of the same order. The relative larger value makes the plate bend upwards. The compressive plastic strain on the bottom surface releases the restraint coming from the neighboring material, so that the remaining elastic strain on the top surface (within plastic zone) is compressive. A similar phenomenon is also found in buckling mechanism (BM) laser forming, and it provides an effective way of removing the tensile longitudinal residual stress. This is explained in the following section.

Characteristics of LF-induced Distortion and Residual Stress

There are three types of mechanisms (Temperature Gradient Mechanism-TGM, Buckling

Mechanism-BM, upsetting mechanism-UM) were reported in laser forming (Vollertsen, 1994). The TGM is the most widely used laser-bending mechanism. A large temperature gradient through the thickness direction makes the plate bend upwards. TGM can be utilized to remove the angular distortion in the correction process. In the BM, the laser beam diameter is on the order of ten times the sheet thickness, resulting in a relatively low temperature gradient in that direction. Due to heating, thermal compressive stresses develop in the sheet which results in a large amount of thermo-elastic strain which in turn results in local thermo-elasto-plastic buckling of the material. It is found that through buckling mechanism (BM) laser forming, compressive residual stresses perpendicular to the weld path are induced (shown in Fig. 5). To reduce the welding-induced tensile longitudinal stress, so as to reduce the caused longitudinal distortion, BM laser forming should be applied.

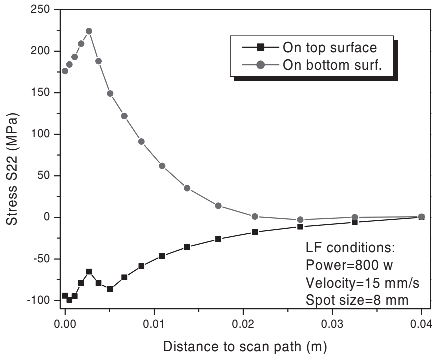

FIGURE 5. TRANSVERSE RESIDUAL STRESS INDUCED BY BM LASER FORMING

The reason that BM laser forming induces compressive transverse stress can be found from the time history of the transverse residual stress. The transverse stress initially increases from zero before the heating source reaches. This is because that the material tends to expand when the heat source is approaching, and the extension strain is only elastic since the temperature is low before heat source reaches. During heating, compressive stresses arise because of the restraint due to the surrounding material and cause local buckling of the sheet because of the geometry of the heated area. When the temperature still increases, the flow stress of the material goes down. Whereas the material in the centre of the buckling area is plastically deformed, the deformation at the sides is still elastic. The neighboring area in the direction of the path feed is already elastically buckled out, whereas the area behind is plastically formed. The restraint of the surrounding material decreases as the beam approaches the second edge. The elastic counter bending of the sides goes down and the bend angle arises. Fig. 8 shows the typical residual stress distribution for the BM laser forming.

Overall Strategy

The overall strategy for welding distortion correction by laser forming is summarized in the following. Firstly the welding-induced distortion can be decomposed into two components: angular distortion and longitudinal distortion. The former distortion can be expressed as bending angle and measured by coordinate measurement machine (CMM). For the longitudinal distortion, the surface displacement and residual stress can be measured by CMM and XRD. The angular distortion can be removed by TGM laser forming, while the longitudinal distortion can be removed by releasing the tensile residual stress along the longitudinal direction through the BM laser forming.

To remove the angular distortion, the laser-forming path should be along the weld path and applied on the bottom surface. To remove the longitudinal distortion, BM laser forming should be applied on the top surface and the scanning paths are perpendicular to the weld path. The heating conditions (including laser power, scanning speed and beam spot size) can be determined through the database established by FEM. In the database, the bending angle and the transverse residual stress are functions of laser power and scanning speed under the condition of TGM (at a smaller beam diameter and relative large scanning speed) and BM (at a larger beam diameter and relative smaller scanning speed), respectively. By matching the angular distortion and the residual stress between the required values and those of database, the laser power and scanning speed can be determined uniquely if the beam spot size and path spacing are given. Multiple scans may be applied on the same paths if the distortions are not reduced to a critical level. This methodology will be explained in more detail in the following sections.

LF Correction on Straight Line Bead-on-plate Welding

Fig. 6 shows the designed paths for the correction of distortion induced by straight line bead-on-plate welding. The path for the angular distortion correction is applied along the weld path on the bottom surface. The paths for the longitudinal distortion correction are applied perpendicular to the weld path and located with equal spacing. In determining the spacing of adjacent scanning paths, a number of guidelines are followed. In general, the paths at the regions that have larger longitudinal residual stresses should have denser spacing than regions of smaller stresses. At the same time, due to the practical restrictions such as the cooling issues, the spacing cannot be too close. The spacing between two adjacent paths, d_{LF}, should be equal to the average transverse stress generated by laser forming, $\bar{s}_{laser}$, multiplied by the size of heat-affected zone, d, and divided by the welding-induced longitudinal stress over the spacing, written as

$$d_{LF} = \bar{s}_{laser} d / \bar{s}_{required} . \tag{4}$$

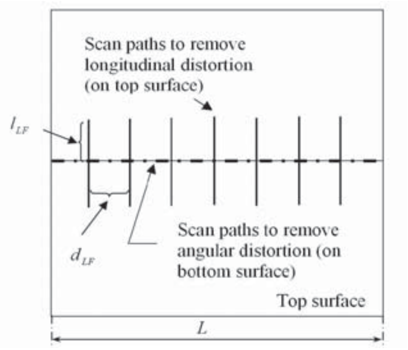

FIGURE 6. SCANNING PATHS OF LASER FORMING TO REMOVE DISTORTIONS

If the laser-generated residual stress $\bar{s}_{laser}$ can fully match the required stress within the range of the heat affected zone (HAZ), the width of HAZ can be adopted as the initial path spacing. The spacing of the paths may vary if the welding induced longitudinal stress varies along the weld path. If this strategy results in a path spacing that is too large to be covered by LF-generated strain, additional scanning paths should be added. The length of the BM laser-forming path, l_{LF}, can be determined based on the coverage width of the welding-induced longitudinal stress. The coverage width, l_W (shown in Fig. 4), can be defined as the region within which the tensile longitudinal stress is at least 5% of the maximum value occurring in the weld path.

Fig. 7 shows the database that bending angle is a function of laser power and velocity under the condition of TGM. The beam diameter is assumed as constant (i.e., d=4mm). By matching the welding-induced value and the LF-generated value, a group of heating conditions (P and V) can be determined. In general, the combination of large P and V is preferred since it can increase the working efficiency. If the welding-induced bending angle is too large to be recovered by single scan laser forming, multiple scans should be used to avoid melting or material damage. Similarly, the heating conditions for removing the longitudinal tensile stress can be determined from the database in which the LF-generated residual stress in the direction perpendicular to the scanning path is a function of P and V.

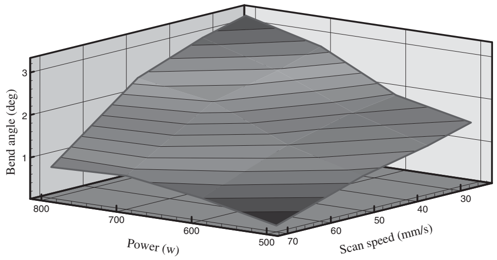

FIGURE 7. PROCESS MAP TO DETERMINE THE HEATING CONDITIONS

Experiments were conducted on 1010 steel coupons with dimension of 80x80x0.89mm. The scanning paths and heating conditions in the experiments were determined as described above. The laser beam diameter on the top surface of workpiece is 4mm for angular distortion correction, and 8mm for longitudinal distortion correction, respectively. Fig. 8 shows the comparison of distortion before and after LF correction under these conditions. Only the top surface of the plate is measured and compared. It is found that over 70% of the angular and longitudinal distortions have been removed. The remained longitudinal residual stress on the top surface is also measured by XRD. About 50% of the tensile residual stress on top surface is removed. The correction procedure is also numerically modeled and good agreement is achieved compared to the experimental result.

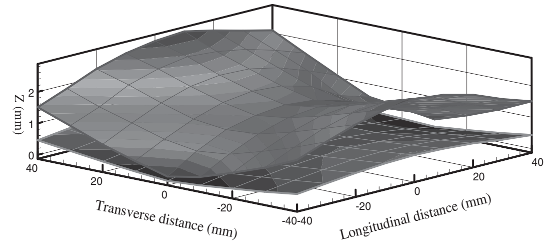

FIGURE 8. COMPARISON OF DISTORTIONS BEFORE AND AFTER LF CORRECTION

LF Correction on Non-straight Path Bead-on-plate Welding

Fig. 9 shows the measurement of distortion on a circular-path bead-on-plate welding sample. A saddle shape with negative Gaussian curvature is observed. The distorted shape after welding is mainly due to the moving heat source and its scanning direction. From the measured bending angle along the weld path (Fig. 10), it is found that the bending direction changes along the path. The reason is due to the adjacent bending effect which is induced by moving heat source, and also due to the direction change of the major inherent mechanical constraint. This non-uniformity is greatly affected by the scanning speed. Assuming an extreme case, that the scanning speed is so fast that the heating energy input is almost instantly applied on the circular path, the bending direction will be the same and toward the heating source.

FIGURE 9. DISTORTIONS INDUCED BY CIRCULAR PATH WELDING

Four regions are divided according to the bending direction. The size of each region is not uniform; the region with positive bending angle (bending towards the heat source) is larger than that of the negative bending angle. The paths for correcting the angular distortion are still applied along the weld path, but it is on a different surface in a different region dictated by the direction of the bending angle. In regions I and III with positive bending angle, the laser-forming path is on the bottom surface, while in regions II and IV with negative bending angle, the LF path is on the top surface. Since the longitudinal tensile residual stress is almost constant along the weld path, the laser forming paths to correct the longitudinal distortions can still be equally-spaced, and are applied on the top surface. All the paths on this circular-path bead-on-plate welding are shown in Fig. 11.

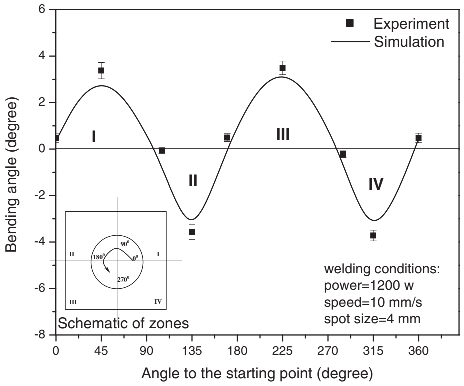

FIGURE 10. DISTRIBUTION OF ANGULAR DISTORTION INDUCED BY CIRCULAR PATH WELD

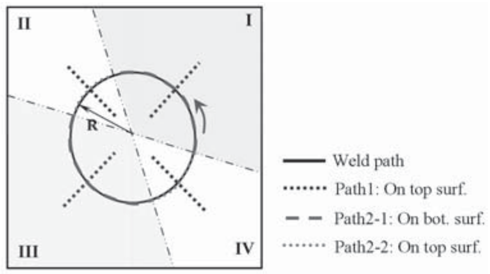

FIGURE 11. DESIGNED CORRECTION PATHS FOR CIRCULAR PATH WELDING

Noticing the large variation in bending angle within each region (i.e., region I), the LF scanning path must still be divided into several segments. In each segment, the bending distortion can be treated as constant. Then referring to the heating condition databases, the required laser power and scanning speed can be determined. For the circular-path case, the longitudinal stress inside the circle is larger than that of the outside due to the overlapping accumulation. This requires that the paths for correction of longitudinal residual stress also be divided into 2 segments that are separated by the circle path. The heating conditions can then be determined inthe same manner used above. Fig. 12 shows the comparison of the welded distortions before and after LF correction. It is seen that most of the angular and longitudinal distortion was removed. Better removal of the angular and the longitudinal distortion can be achieved by dividing more segments along the circular path, and adding more paths which are perpendicular to the circular welding path, respectively.

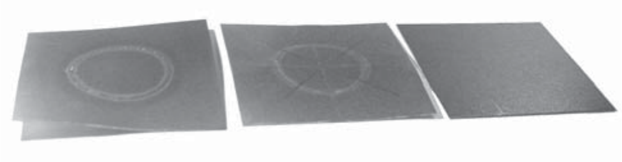

FIGURE 12. EXPERIMENTAL VALIDATION FOR LF CORRECTION OF NON-STRAIGHT PATH WELDING

Further Discussion

For complex welded structures, the welding induced distortion may not be easily decomposed into angular distortion and longitudinal distortion. For those cases, the strain-based methodology which is already applied to the laser forming process design (Cheng and Yao, 2005) may be a good way to design the correction conditions (including both heating paths and heating conditions). The general principle can be described as follows. From the initial shape and the distorted shape, the strain field that needs to be removed can be calculated through elastic FEM simulation. Accounting for the characteristics of laser forming, in that the generated strain is mostly perpendicular to the scanning path and is compressive, the LF scanning path can be determined on the concave side and is perpendicular to the principal minimum strain direction. The corresponding heating conditions can be determined through the databases established by FEM simulation as well. The challenging issue in this methodology is how to account for the welding induced residual stress when determine the required strain field.

CONCLUSIONS

In this study, the welding distortions induced by straight- and non-straight paths are effectively corrected by the laser forming approach. The out-of-plane distortion can be decomposed into angular distortion and longitudinal distortion. The former can be removed by laser forming under TGM condition. From the characteristics of buckling mechanism (BM) laser forming, it is found that the LF-generated compressive stress can be used to remove both the tensile longitudinal residual stress and longitudinal distortions. The result shows that laser forming can be used to effectively remove the distortions induced by butt welding.

ACKNOWLEDGMENT

The work is supported by NIST under grant ATP-00005269.

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