# Numerical study of the residual stress field during arc welding with a trailing heat sink

F. A. Soul & Z. Yanhua
*School of Mechanical Engineering,*
*Beijing University of Aeronautics and Astronautics, China*

## Abstract

The arc welding process is widely used in areas such as the aerospace industry, shipyards and others. The stress and distortion induced by the arc process is high compared with other fusion welding processes such as LBW or EBW. This paper presents the numerically predicted results of a study aimed at establishing the temperature distribution, distortion and the residual stress field developed during the conventional welding process and after enhancement with a trailing heat sink. A numerical analysis of the thermo-mechanical process using FEM by means of ANSYS code was carried out. The analysis results obtained showed that this technique strongly improves the welding process by means of minimizing the residual stress and distortion especially when small thicknesses were applied. It was found that the distance between the welding arc and the cooling one is an important factor for improving results.
*Keywords: arc welding, temperature field, residual stress, distortion.*

## 1 Introduction

The highly localized transient heat and strongly non-linear temperature fields in both heating and cooling processes cause non-uniform thermal expansion and contraction, and thus result in plastic deformation in the weld and surrounding areas. As a result, residual stress, strain and distortion are permanently produced in the welded structures. High tensile residual stresses are known to promote fracture and fatigue. Longitudinal tensile residual stresses may induce undesired distortion such as cambering (Fig. 1).

There is no way to control these phenomena during the welding process only by applying some technique. Through the last decades mechanical tensioning

[1,2] and thermal tensioning [3,4,5,6] have been suggested in thin section structure for controlling welding residual stress and hence distortion. These tensioning processes involve generating tensile strain at the weld zone during welding by either mechanical tensioning or by imposing a preset temperature gradient. However, the mechanical tensioning method is impractical for industrial implementation because it requires large forces and a complex set-up. A novel controlling technology of Low Stress No-Distortion (LSND) has been developed at the Beijing Aeronautical Manufacturing Technology Research Institute in China as schematically shown in Fig. 2.

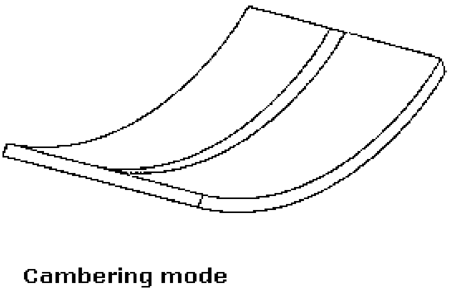


Figure 1: Cambering distortion mode induced by welding.

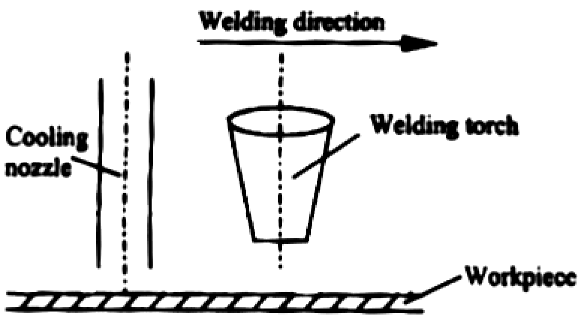


Figure 2: Scheme of the heat sink process.

The process has been applied to jet engine cases of heat resistant alloys and rocket fuel tanks of aluminium alloys [7]. In this technique, a heat sink trails behind the welding arc in such a way that their thermal fields interact, significantly reducing the residual stresses and distortions created by the GTAW process. The process is flexible and non-linear so a complex welding path can be achieved. Using this process, the residual stress and distortion successfully controlled during manufacturing in practical production was established [8]. Since the heat sink is always moving after the welding arc during this novel welding process, this welding method is also called dynamically controlled low stress no-distortion (DC-LSND) welding technology [9]. Although this technology has been proved to be valid in stress and distortion control, there is no detailed work to study the control mechanism of this technology, nor systematic work to investigate how every technological parameter influences the control effects. So extensive work may be needed to establish a better understanding for the process mechanism.

Concerning the (DC-LSND) welding technique, in this paper numerical simulations were applied to investigate the detailed thermo-mechanical behaviour during this process using 3-D FEM, and to analyse how the process can control the residual stress and bending distortion. The main objective is to get an engineering expression for the control mechanism of this technique, which may put new initiative in future and enlarge its applications.

## 2 Numerical modelling

### 2.1 Analysis procedure

A bead on a thin plate of aluminium alloy (5083) was employed in the numerical analysis. The sheet dimensions are 250 mm long, 80 mm width and 3 mm thick. Both conventional GTAW process and after enhanced by trailing heat sink are investigated. To find the effective penetration of the cooling through the thickness, two other thickness of 4 mm and 5 mm samples were analysed. The welding parameters and related physical quantities in addition to the heat sink parameters used in FEA are listed in Table 1.

Table 1: Welding parameters and related physical properties.

| Parameter | Value |
|---|---|
| Welding current, A | 160 |
| Welding voltage, V | 15 |
| Arc efficiency, % | 65 |
| Welding speed, mm/s | 6 |
| Ellipsoid parameters., $a_1$ , $a_2$ , b, c, mm | 5,20,10,2 |
| Thermal conductivity of cooling media[13], $Wm^{-1}K^{-1}$ | $63.4\times10^{-2}$ |
| Diameter of cooling nozzle, mm | 1.4 |
| Heat sink effective radius, mm | 5 |
| Distance between arc and heat sink, mm | 22,26,30 |
| Cooling media flow rate, $mm^3s^{-1}$ | $6.67\times10^{4}$ |
| Nusselt number | 1317.5 |

The temperature dependent material properties of used material were taken from [10]; due to symmetry a half of the model is analysed using the mesh division shown in Fig. 3.

#### 2.1.1 Moving heat source and trailing heat sink

Heat generation in welding is based on the concept of instantaneous heat sources. The heat source model developed by Goldak et al. [11] is used in this research, which distributes the heat throughout the volume of the molten zone. The Goldak heat source model is defined spatially by a double ellipsoid, which is well suited for modelling a weld pool where heat distribution is dominated by fluid flow.

Figure 3: Finite element model.

The use of heat sink makes the metal cool rapidly from a high temperature in a local zone in which results low stress and no distortion [9]. For this reason the numerical analysis is necessary to understand the mechanism for the occurrence of this minimization. The cooling media can be fluid or gases, which do have a metallurgical affect on material. Simulation of the intense cooling effect is expressed in [12]; the heat transfer between the specimen and the cooling media is described with the impinging jet heat transfer model [13]. The average Nusselt number for the convection heat transfer between the cooling media and specimen $\overline{Nu}$ should be calculated according to the formula presented in [12]. Then, the average heat transfer coefficient $h$ between the atomised cooling jet and the sample top surface can be obtained by this equation:

$$h = \lambda \overline{Nu} / D \tag{1}$$

where $\lambda$ is thermal conductivity of the atomised media and $D$ is the diameter of cooling nuzzle.

### 2.1.2 Thermal-elastic-plastic analysis

After the thermal analysis is done, sequentially coupled thermo-mechanical analyses were performed. The model was performed as an elasto-plastic analysis with isotropic strain hardening. The mechanical constraints imposed on the models consisted of a symmetry condition across the plane of the nodes along the weld path and a pin joint at some edge nodes. These constraint conditions are allowing free deformation of the sample during welding.

## 3 Result and discussion

The temperature distribution result from the thermal analysis for the heat sink process stated above is predicted at a welding time of 25s from welding and presented in Figure 4. The temperature decreases drastically in the zone between the arc and the heat sink, and the corresponding temperature gradient increases.

In fusion welding the temperature and corresponding stress and strain cycle are completely different for different locations in the sample due to non-uniform heating and cooling processes. However, to distinguish these differences in both conventional and after applying heat sink processes, several locations on the same path perpendicular to the weld centerline and at the length of (X=140 mm) were selected for analysis.

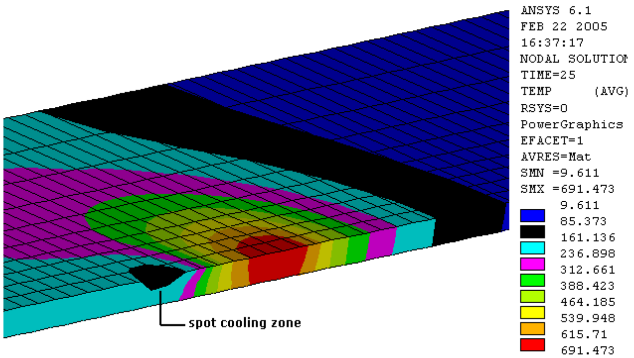


Figure 4: Temperature contour after 25s with moving spot heat sink.

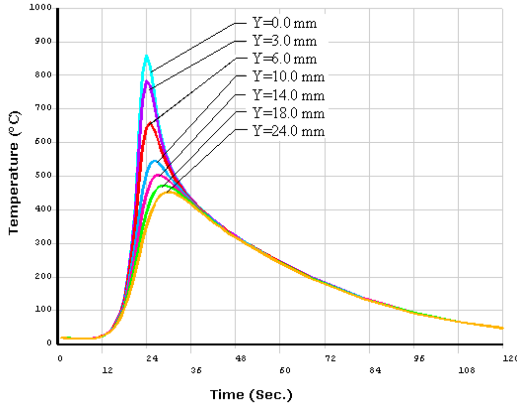


Figure 5: Thermal history in conventional welding process.

Figs. 5 and 6 both depict thermal history developed in the welding process. The thermal history of the selected locations in the dynamic spot heat sink technique (Fig 6) revealed that the points relatively far away from the weld centerline are quite similar to those of the corresponding points in conventional welding. The only difference is that the temperature value in welding with trailing heat sink is somewhat lower from those in conventional welding. However, the thermal history of the points at or close to the welding centreline seem much different to those of corresponding points in conventional welding.

Moreover, due to the presence of trailing heat sink, an intense temperature decrease can be found from the thermal history curves of the points within the action of spot heat sink. It is interesting to note from the points at and near to the weld centerline, that the duration time for the metal staying at a high temperature in the trailing heat sink process is much shorter than in the conventional process.

The proper way to characterize the stress developed during the two welding processes is by analyzing the transient stresses.

Points in the welding centerline were selected to demonstrate the transient stress at upper and lower surfaces at different positions along the welding path, but more attention in this analysis is made at the mid length of the model.

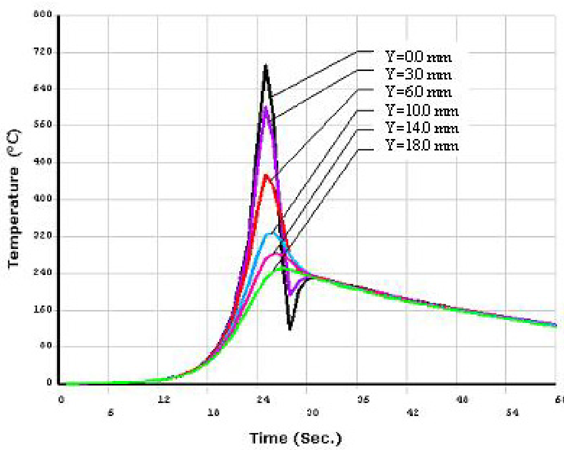


Figure 6: Thermal history in trailing heat sinks process.

Figs. 7 and 8 shows the transient longitudinal stress in both processes. In the conventional welding process the stress change is from compression in front of the heat source to tension behind it, in this stage the temperature drops down under the normal cooling rate and the metal begins to contraction so the tension stress increases according to the decreasing of the temperature. The maximum value for residual stress can be observed in the mid-thickness and exceed that in the upper surface by about (~10 MPa) at some regions along the welding line. Further, the upper and lower surfaces residual stress reveal very small differences between them. However, these differences are not stable along the welding line, at some distance from start point (X= 0.0 mm), the upper surface stress exceeds the lower and at other distance the opposite is true.

This may be due to the rate ability of material stiffness resistance that can vary from region to region with respect to the time of welding and stress developed in the previous steps.

In the result in Fig. 8, obtained when the trailing heat sink is located at 30 mm behind the torch, the transient longitudinal stress graph shows different behaviour from those in convention welding. As soon as the heat sink zone arrives at the selected analysis region, the tensile stress increases rapidly to a somewhat high value, then decreases steeply to a minor value and finally it increases again to residual value. The decrease in stress magnitude may be due to the release of some stress behind the cooling. In more detail at the heat sink region the metal temperature suddenly drops from a higher temperature with a high cooling rate by the action of cooling media, This rate of cooling generates high contraction for the metal in this zone and seems to increase the tensile stress value in a short time as depicted in fig. 8. However, as soon as the heat sink crossed the region, the temperature rises again behind the trailing heat sink due to the surrounding metal temperature. In this case, the process became as the tempering after quenching and the metal seems to expand due to heating which is believed to repeat the expansion process in the metal. Furthermore, at this stage some of the strain may be released due to heating, thereby the tensile stress value decreases again to a somewhat lower value.

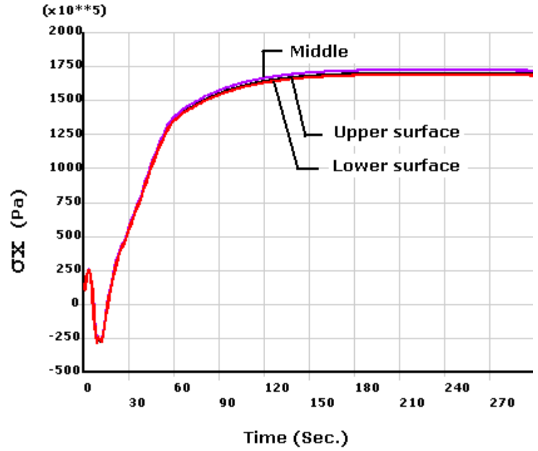


Figure 7: Transient longitudinal residual stress in conventional welding process.

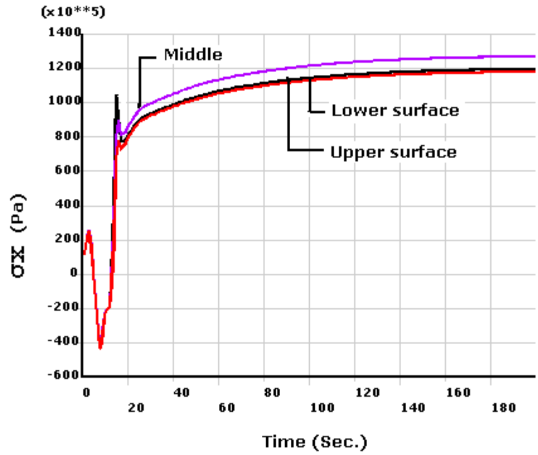


Figure 8: Transient longitudinal residual stress in moving spot heat sink.

The maximum longitudinal residual stress in the heat sink process was minimized at about (~55 MPa) from that in conventional welding. The significant interest in Figs. 7 and 8 is that most of the residual stress in the trailing heat sink was developed in a short period of time compared with that developed in the conventional process. These differences give a good representation according to the thermal history result obtained in Figs. 5 and 6. In the welding process, the residual stress value is based on the inherent strain or plastic strain, so the analysis of strain behaviour is important to characterize the minimization of residual stress. In this paper there is no way to introduce the behaviour of plastic strain developed in the novel technique in more detail, but it will be present in another paper. However, the plastic strain developed in the heat sink process also differs from that in conventional welding and it's magnitude was reduced about twice after applying the trailing heat sink process, From the above result it can be concluded that minimization of the residual stress in trailing heat sink process refers to the reduction in the plastic strain.

Fig. 9 shows the effect of distance between the heat source and the cooling source on the longitudinal residual stress. There is an improvement for residual stress minimization at an appropriate distance. more statistical analyses are needed to find the optimum distance which gives the minimum value of residual stress.

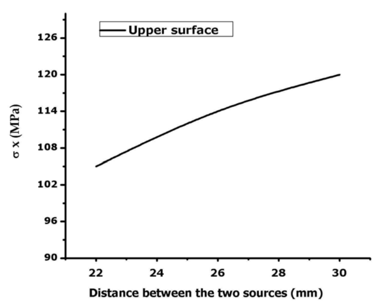


Figure 9: Effect of distance between the sources on the residual stress.

Concerning the cooling process, the longitudinal residual stress at the mid-distance through the thickness was critically affected by the thickness of the sheet. Obviously, as the thickness decreases, the residual stress may decrease due to the excess of cooling penetration in the thin section. It can be concluded that the process became more active as the welded sheet thickness decreased.

Fig. 10 show the comparing of the final distortion in computed and experimental, the measured maximum displacement at the mid-plate length centreline is (~4.9 mm), the computed one is reasonable with that appearing in the experiment along the welding line, and only lowering about (0.4mm) at the middle. However, when the welding is enhanced with trailing heat sink the maximum displacement is (~0.2mm). It is found that there is significant decreasing in displacement and the model does not reveal bending. It is believed that by regulating the heat sink parameters, the longitudinal residual stresses were minimized to a value which cannot affect the structure rigidity and therefore the bending distortion may be eliminated.

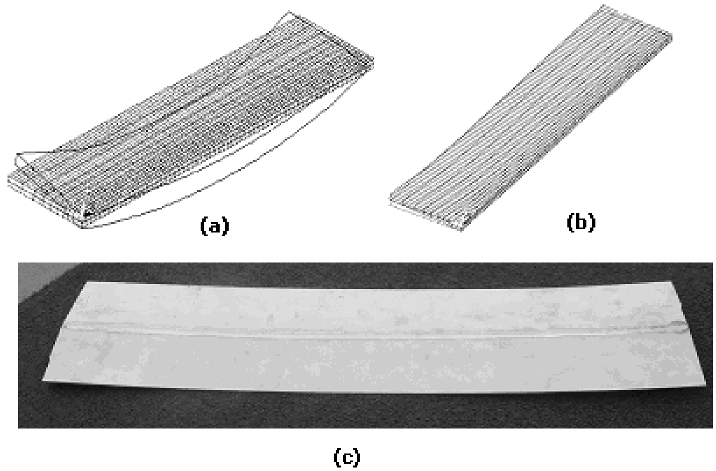


Figure 10: Final distortion a- conventional process; b-with heat sink process; c-welded experiment sample.

## 4 Conclusions and further work

Using the trailing heat sink technique, low temperature values exist in the thermal history curves for the points at and close to the weld centreline, the duration time at high temperature of these points are much shorter than in the conventional welding. Transient longitudinal residual stress curves in the heat sink technique show different behaviour from that in conventional welding and the residual stress is significantly reduced. By controlling the process parameters the residual stress magnitude became insignificant to produce distortion and hence cambering distortion can be eliminated.

3-D finite element analysis gives realistic representation for modelling trailing heat sink enhanced heat transfer, and better characterisation for stress history through thickness. Further work is needed for different materials to become better understood for heat sink mechanism.

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